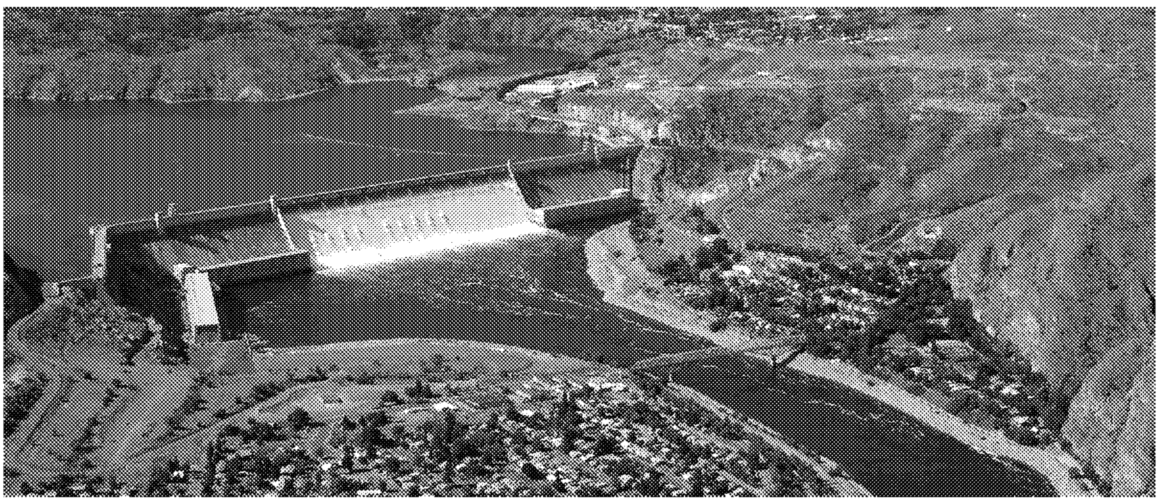
RECLAMATION
Managing Water in the West

Thermal Regime of the Columbia River at Lake Roosevelt



U.S. Department of the Interior

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Bureau of Reclamation

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

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Ex. 5 Deliberative Process (DP) Others, like Franklin D. Roosevelt Reservoir (commonly referred to as Lake Roosevelt) retain much of their run-of-river thermal characteristics due to the very high volume of flow passing through the reservoir in a relatively short period of time. Ex. 5 Deliberative Process (DP)

Ex. 5 Deliberative Process (DP)

Key concepts discussed in this paper include:

1. Inflow and outflow temperatures at Grand Coulee Dam - Compared to inflow temperatures at the International Boundary, Grand Coulee releases tend to be warmer September through January, slightly cooler in February through July, and cooler July through August. In 2015 Grand Coulee releases were warmer from October through January, roughly equivalent February through April, slightly cooler March through July then warmer August through September.

2. Weak Stratification – Relatively short retention times in Lake Roosevelt (ranging from 11 days on average in May to 38 days on average in October) present a key limiting factor for stratification (temperature variation at depth). The reservoir exhibits only a weak stratification during the summer months, with the largest temperature gradients occurring near the surface. Much stronger stratification would be necessary for meaningful thermal mitigation for the lower Columbia River from Grand Coulee operations.

Operational Flexibility - Limited flexibility to change operations between powerhouses (i.e. release water from different depths in the reservoir) – The intakes for Left and Right Powerhouses are located 100 feet deeper in the reservoir than the intakes for Third Powerhouse. Ex. 5 Deliberative Process (DP) Ex. 5 Deliberative Process (DP) The units in Left and Right Powerhouse are operated continuously while the units in the Third Powerhouse are cycled on and off for peaking operations.

Ex. 5 Deliberative Process (DP)

1 INTRODUCTION

Water temperature regimes are important to the timing and survival of salmon and steelhead migrating through the Columbia River Basin. Ex. 5 Deliberative Process (DP) anadromous fish species, Ex. 5 Deliberative Process (DP), highlight the need for fish managers and water managers to investigate potential actions that would reduce water temperatures, thus reduce risk to migrating fish. Ex. 5 Deliberative Process (DP)

Ex. 5 Deliberative Process (DP)

Reclamation uses this paper to further examine the thermal conditions of the Columbia River at Grand Coulee Dam. The purpose of this paper is to summarize seasonal operations, and the current thermal regime for Lake Roosevelt. The summary of the thermal regime includes inflowing and outflowing temperatures, water residence time in the reservoir, and the resulting thermal stratification in the reservoir pool. The information in this paper will provide decision makers with a more complete understanding of the Columbia River temperatures at Grand Coulee Dam.

1.1 Background

Generally, reservoirs can influence water temperature by changing travel time, causing stratification, and increasing surface area exposed to solar radiation. Some dams are equipped with outlets at varying elevations that allow operators to manipulate downstream water temperatures by drawing from specific stratified layers. Operations of Dworshak Dam on the North Fork Clearwater have been particularly successful in this regard, providing significantly cooler water to the Snake River during the warm summer months. However not all reservoirs are capable of providing downstream temperature benefits. Run-of-river and small storage reservoirs (which typically have weak, or non-existent, stratification) usually fall into this category.

Franklin D. Roosevelt Reservoir (commonly referred to as Lake Roosevelt) behind Grand Coulee Dam is a fairly large storage reservoir (5.2 million acre-feet, MAF, active space, 9.4 MAF total space) and has been pointed to by some as a potential source of cool stratified water for the Columbia River; however it often responds more like a run-of-river project.

There have been many studies of Lake Roosevelt describing the limnology of Lake Roosevelt (Vermeyen 2000). **Ex. 5 Deliberative Process (DP)**

Ex. 5 Deliberative Process (DP)

2 LAKE ROOSEVELT AND GRAND COULEE DAM

2.1 Setting and Project Description

Grand Coulee Dam is located on the Columbia River ([REF _Ref498501072 \h * MERGEFORMAT]) at approximately river mile 597. It is the primary component of the Bureau of Reclamation's Columbia Basin Project, which was developed to provide flood risk management (FRM), irrigation, municipal, and industrial water supply, and hydropower generation. Grand Coulee is the largest dam in the Columbia River basin,

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[1] Thermal stratification refers to a change in temperature at different depths due the change in water's density with temperature.

[2] Temperature mitigation can either be adding cool water to the river to reduce temperatures (typically in the summer) or adding warm water to increase temperatures (typically in the winter).

comprised of 12-million cubic yards of concrete, and measuring 550 feet tall and 5,223 feet long (Figure 2.2). The reservoir impounded by Grand Coulee Dam is Franklin D. Roosevelt Lake (Lake Roosevelt), named for the president who authorized construction of the dam. Lake Roosevelt extends 151 miles upstream to the US-Canadian border. Downstream of Grand Coulee the Columbia River flows through Lake Rufus Woods (behind Chief Joseph Dam), multiple Public Utility District (PUD) run-of-river dams (operated by 3 different PUD's, Priest Rapids, and into McNary pool at the confluence with the Snake River.

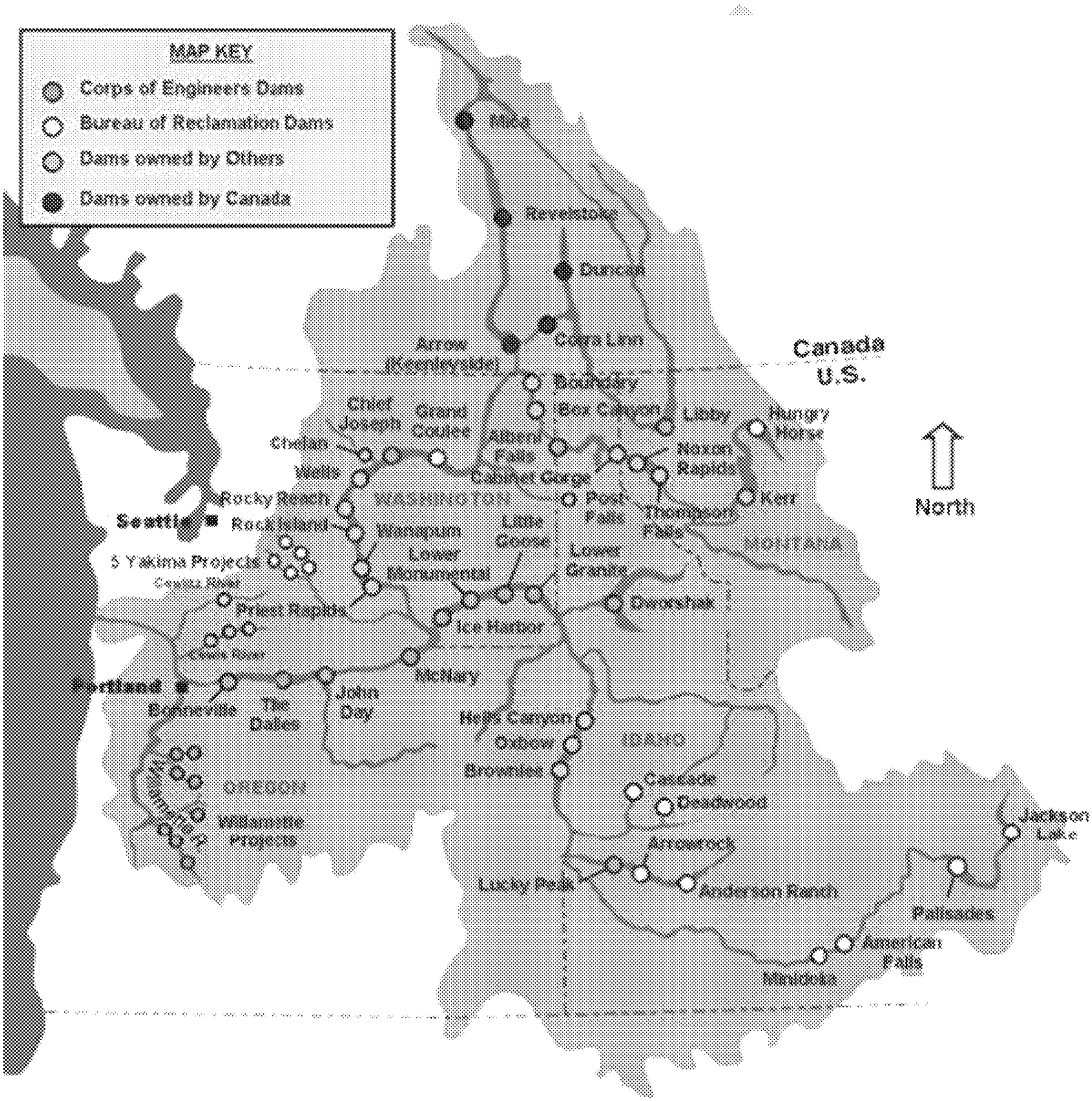

Figure [STYLEREF 1 \s].[SEQ Figure * ARABIC \s 1] Location of Grand Coulee Dam on the Columbia River.

Currently, Reclamation has been authorized by Congress to operate Grand Coulee Dam for the multiple purposes of FRM, navigation, power generation, irrigation, and other beneficial uses including fish and wildlife. In coordination with other FCRPS facilities, Reclamation operates the dam to respond to a variety of factors including water supply conditions, power demand, and flow needs for fish. These factors change from month to month and season to season.

Grand Coulee Dam generates power primarily through the use of the Left, Right, and Third powerhouses ([REF _Ref499103572 \h]). There is a significant difference between the capacity of the units in the Third Powerhouse (approximately 30,000 cfs and 800 MW per unit) and those in the Left and Right powerhouses (approximately 6,000 cfs[3] and 150 MW[4] per unit). As shown by [REF _Ref499103442 \h]it would take five units from the Left and/or Right powerhouse to equal the hydraulic capacity of one unit from the Third Powerhouse. This limits the flexibility to shift operations from the Left and Right to the Third powerhouse or vice versa.

[3] Cubic feet per second (cfs)

[4] Megawatt (MW)

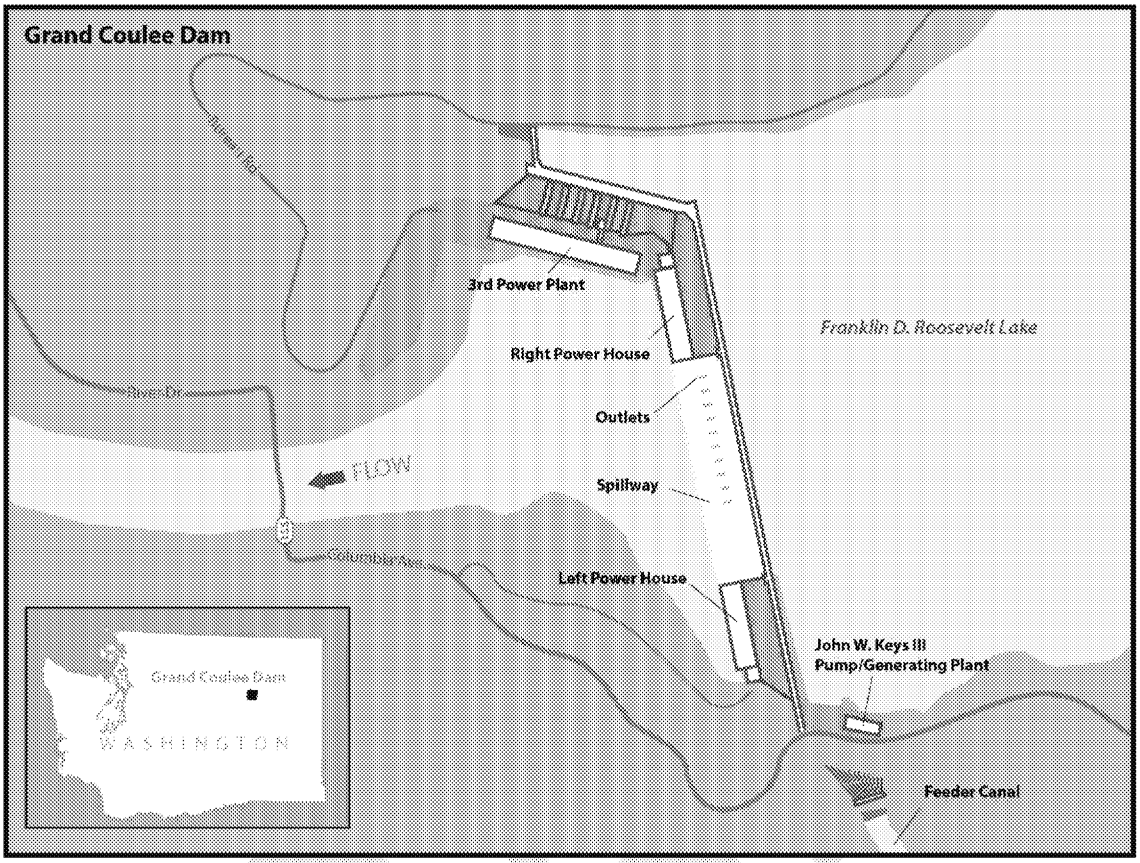

Figure [STYLEREF 1 \s].[SEQ Figure * ARABIC \s 1] Overview diagram of Grand Coulee Dam and key features.

The John W. Keys III pump/generating (JWKIII P/G) plant pumps water from Lake Roosevelt to Banks Lake through 6 pumps and 6 pump-generators (P/G) to supply water to the Columbia Basin Project (CBP) for irritation and municipal/industrial (M&I). JWKIII P/G can also be used to generate power by running water from Banks Lake to Lake Roosevelt through the 6 P/G units.

Table [STYLEREF 1 \s].[SEQ Table * ARABIC \s 1] Powerhouse summary of hydraulic capacity and intake elevation

Powerhouse	Approximate Intake Elevation (feet)	Approximate Hydraulic Capacity per unit (kcf)	Approximate Hydraulic Capacity per unit (MW)	Approximate Total Powerhouse Hydraulic	Approximate Total Powerhouse Hydraulic

				Capacity (kcfs)[5]	Capacity (MW)[6]
Third (6 units)	1140	30	800	120	3200
Left (9 units)	1040	6	150	42	1050
Right (9 units)	1040	6	150	42	1050

2.2 Grand Coulee Current Operations and Constraints

The operations of Grand Coulee Dam respond to a variety of factors including water supply conditions, power demand, and flow needs for fish. The combination of operational purpose and variable conditions result in pool elevation ([REF _Ref499103658 \h]) and flow changes hourly, daily and seasonally.

[5] With assumed outages of 2 units in each powerhouse for maintenance.

[6] With assumed outages of 2 units in each powerhouse for maintenance.

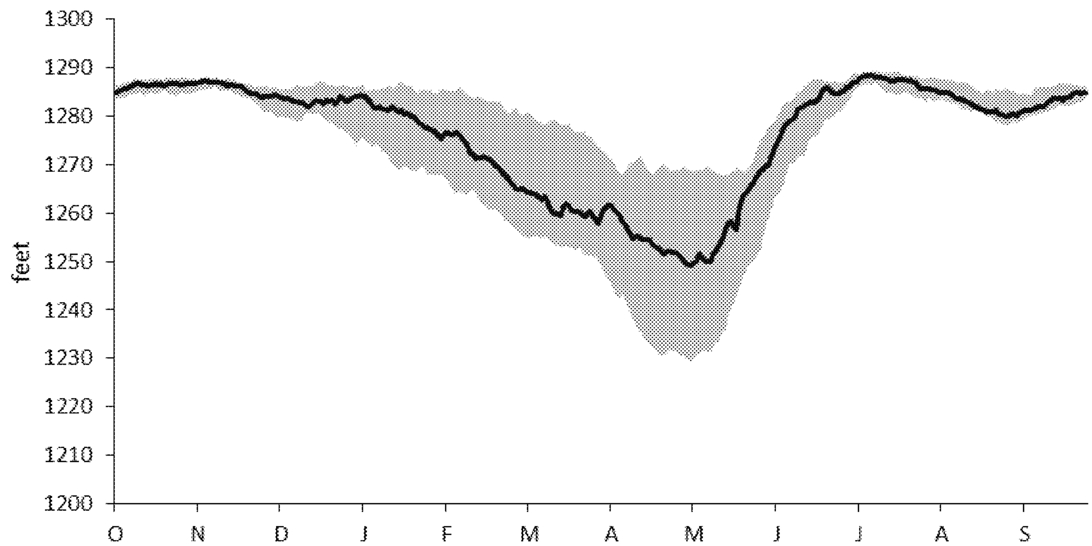

Figure [STYLEREF 1 \s].[SEQ Figure * ARABIC \s 1] Lake Roosevelt surface elevations, showing the median, 20%, and 80% exceedance for water years 1986 through 2016.

2.2.1 Fall Operations

During the fall season, Reclamation's operating priorities are power generation and supplemental flows for anadromous fish. By the end of September, Reclamation attempts to refill Lake Roosevelt to a minimum elevation of 1,283 feet to support resident fish in the reservoir. Beginning in October, Reclamation operates Grand Coulee Dam primarily for two purposes: to support tail water[7] elevations for fish as necessary (such releases support spawning and incubation elevations for lower Columbia River chum salmon below Bonneville Dam and spawning and protection flows in the Hanford Reach below Priest Rapids Dam for fall Chinook salmon) and to meet power needs (Grand Coulee's portion of the Firm Energy Load Carrying Capacity, or FELCC). During the fall, Reclamation limits any drafts for power to an elevation of 1,283 feet in October, 1,275 feet by the end of November, and 1,270 feet by the end of December. These elevation limits provide protection for resident fish, chum spawning/incubation below Bonneville, and BiOp refill (to augment flows during the spring and summer period for migrating salmon).

[7] Tail water is the water immediately below the dam.

2.2.2 Winter Operations

During the winter season, Reclamation's operating priorities are FRM, power generation, and minimum flows for fish. Reclamation generally drafts Lake Roosevelt below the required FRM elevations for the purpose of generating power. Such drafts are part of a strategy referred to as "winter power flexibility" and are used to help meet winter power demands in the northwest. Variable Draft Limits (VDL's) allow Lake Roosevelt to provide "winter power flexibility" while providing an 85 percent probability of achieving the April 10th pool elevation objective[8]. The April 10 pool elevation is intended to shape spring flows to benefit juvenile anadromous[9] fish migration. Lake Roosevelt can be drafted below the April 10 elevation to help provide protection flows for Hanford Reach fall Chinook salmon redds[10].

Drum gate maintenance is planned to occur during March, April, and May, annually. The reservoir must be at or below elevation 1255 feet to accomplish this work. Although the maintenance is performed starting in March, the reservoir must be operated starting in February to ensure the reservoir is drafted to at least elevation 1255 feet by mid-March. Although this maintenance activity does not occur every year it must occur at a minimum 1 in 3, 2 in 5, and 3 in 7 years. This activity is completed every year that FRM causes the reservoir to be at or below 1255 feet so that this activity can be avoided in dry years. In dry years, it is important to keep the reservoir as full as possible to augment spring flows for migrating juvenile salmon.

2.2.3 Spring Operations

During the spring season, Reclamation continues operations for the purposes of FRM and power operation and begins operations for spring flow augmentation and irrigation.

As spring flow increases, Reclamation captures some of this flow to refill the reservoir, while continuing operations to support flow augmentation for juvenile salmon and steelhead migrating downstream. Irrigation withdrawals don't begin until late March and then remain relatively light until April. Reclamation delivers over 3 million acre-feet of water annually to irrigate over 758,700 acres within the Columbia Basin Project (CBP).

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[8] The April 10 elevation is an RPA in the 2008/2010/2014 FCRPS NOAA Fisheries Biological Opinion and is based on the Upper Rule Curve (used to operate the reservoir for FRM purposes).

[9] Anadromous fish, such as Pacific salmon species, that migrate from salt water to spawn in fresh water.

[10] A redd is the spawning nest made by fish, specifically salmon.

Water is supplied to the CBP through Banks Lake located adjacent to Grand Coulee Dam, extends approximately 27 miles towards the southwest. Lake Roosevelt must be at elevation 1240 feet by the end of May for the pumping plant to deliver full irrigation demand to Banks Lake. When Lake Roosevelt is below elevation 1240 feet, all six of the pump/generators are inoperable.

During spring or early summer when required releases exceed power demand or unit availability, water must be spilled (bypassing the turbines) at some of the Columbia and Snake River powerplants[11] (known as involuntary spill[12]). Spill past the turbines generate total dissolved gas (TDG) which can be detrimental to aquatic species. The Clean Water Act (CWA) established TDG standards that operators attempt to stay below. As different projects generate different levels of TDG, a spill priority list has been established to help guide operators on where and how much to spill during periods when discharge is higher than the demand. Above an elevation of 1,265.5 feet at Lake Roosevelt, water can be spilled over the drum gates; below this elevation, water must be spilled through the outlet works which consist of both upper and mid-level outlets. These outlets generate a significant amount of TDG and are therefore used only when absolutely necessary. In the event that water must be released through these outlets, then special release configurations (such as over/under spill) are used to help reduce the generation of TDG. Involuntary spill operations generally only occur during FRM operations in the spring and early summer, typically April into July. By midsummer, spill is usually not necessary as there is lower outflow and sufficient power demand, and therefore hydraulic capacity, to pass flow through the powerplant.

When Lake Roosevelt is above an elevation of 1,265.5 feet, Grand Coulee will spill water evenly across the 11 spillway gates (drumgates), which produces significantly lower TDG than spilling water through the outlet works. At lower levels of spill, use of the drum gates can actually reduce TDG concentrations.

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[11] Powerplant refers to the entire project power producing complex, powerhouse refers to a specific component of the powerplant, for example the Third Powerhouse.

[12] Involuntary spill is not by choice, but the project needs to release more water than can be put through the units. Some projects (typically those that have fish passage) release spill voluntarily to supports fish migration downstream.

2.2.4 Summer Operations

During the summer season, Reclamation's operating priorities are irrigation, flow augmentation[13] for fish, and power generation. The reservoir typically refills by early July.

Summer flow augmentation draft levels are determined by forecast. The draft begins after the reservoir reaches its fullest point, in early July, and concludes by the end of August. Reclamation will draft Lake Roosevelt to 1280 or 1278 feet by the end of August for the purpose of supporting McNary flow augmentation objectives. If the July final forecast (as defined in the Water Management Plan) for the April through August period at The Dalles is less than 92 million acre-feet, the draft limit [14] is elevation 1278 feet; otherwise, the draft limit is elevation 1280 feet. The August 31 draft limit will be adjusted an additional amount, up to 1.0 feet in non-drought years and 1.8 feet in drought years (as defined by Washington Administrative Code (WAC) 173-563-056) to implement the Lake Roosevelt Incremental Storage Release Program (LRISRP)[15]. The draft of Lake Roosevelt for LRISRP is to supply water for municipal and industrial (M& I), streamflow enhancement, and irrigation in the Odessa area.

As described in [REF _Ref482363971 \r \h], Grand Coulee Dam has three powerhouses: Left Powerhouse, Right Powerhouse, and Third Powerhouse. Generally speaking, all three powerhouses operate at full capacity (taking into account scheduled maintenance outages) during the daily peak-load periods. The Left and Right Powerhouses run fairly continuously (providing baseload) and are used to stabilize voltage during the night. They are also used to fine-tune power generation during the daytime peak-load periods. The Third Powerhouse, which is substantially larger and more efficient than Left and Right powerhouses, is brought online in the morning to meet daytime power load. These load-following or peaking operations are illustrated in [REF _Ref499026427 \h].

Ex. 5 Deliberative Process (DP)

[13] Flow augmentation is a term to describe increased flow released for fish.

[14] Draft limit refers to the pool elevation that meets an operational objective.

[15] Drought years are defined by Washington to be when the March 1 forecast for April through September runoff at The Dalles is less than 60 MAF.

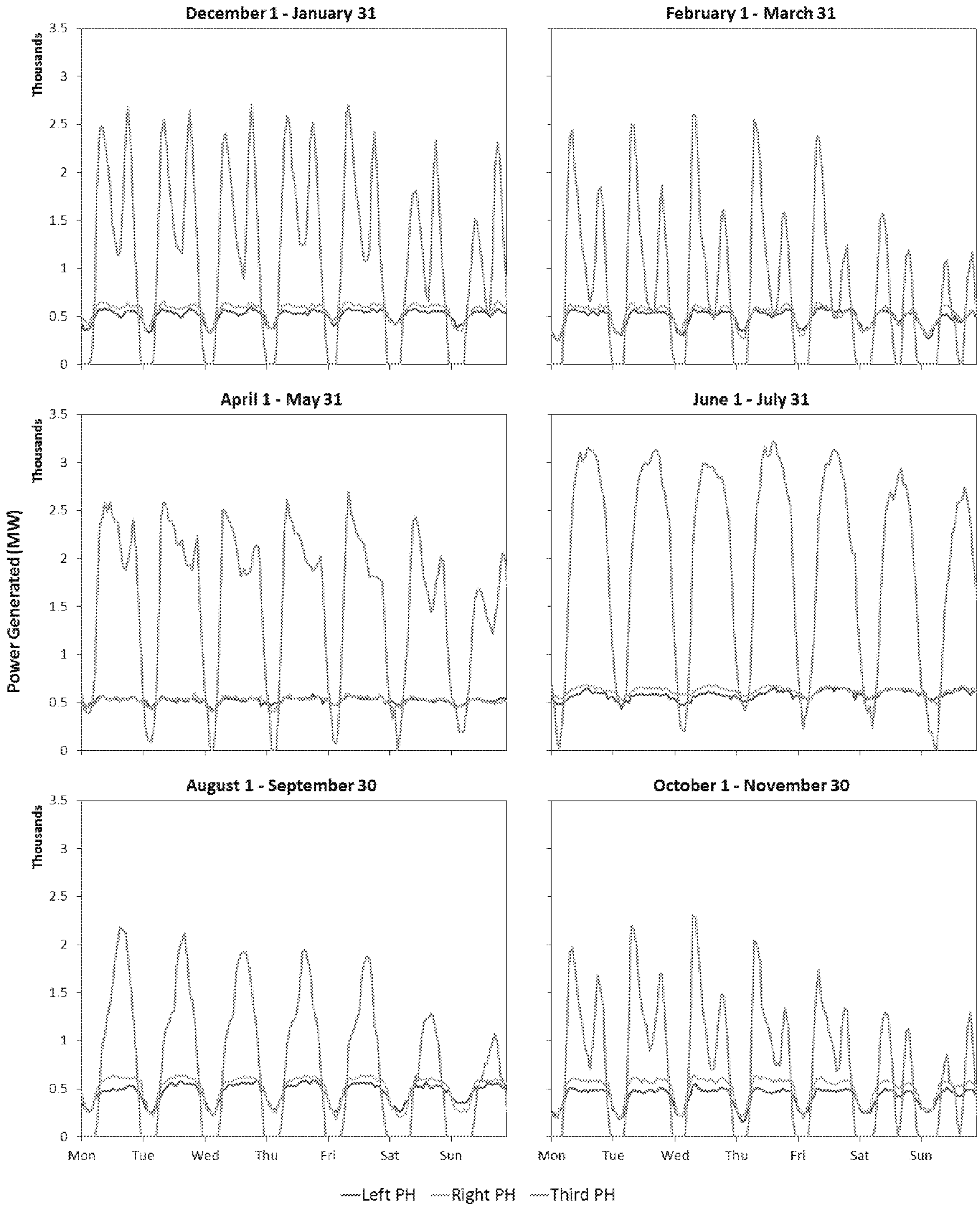

Figure [STYLEREF 1 \s].[SEQ Figure * ARABIC \s 1] Hourly powerhouse operations, Left and Right are used for base-loads, and the Third is used for peaking operations.

Power demands, configuration of the plant, TDG standards, and maintenance outages constrain the flexibility to operate Grand Coulee Dam to modify release temperature. The following list provides a summary of key Powerplant and outlet operational limitations:

- **Power Demand and Voltage Stability**– Power generation at Grand Coulee is directed by the balancing authority to meet the regional power demand. Exclusive use of the Left and Right powerhouses would not provide sufficient power to meet demand. Exclusive use of the large and highly-efficient units in Third Powerhouse would make the 230KV system more vulnerable to power system instability or voltage collapse[16] at the project which would be a major concern for the bulk electrical system of the Northwest.
- **Irrigation Demand** – Power to pump water from Lake Roosevelt to Banks Lake for irrigation of the CBP through the John W. Keys III pump generating plant is generated by units 1, 2, and 3 of the Left Powerhouse. These units cannot be shut down during the irrigation season
- **Peaking Operations** – Daily operations during the spring can vary significantly with daily outflows ranging from 0 cfs to more than 150,000 cfs within a 24 hour period. Exclusive operation of the Third Powerhouse or of the Left and Right Powerhouses do not allow for enough flexibility to meet these peak demands.
- **TDG Production by Non-Powerhouse Outlets** – While the Upper Outlets (elevation 1150 feet) and Middle Outlets (1050 feet) provide additional flexibility with respect to the ability to pass water regardless of power limitations, these outlets generate high levels of TDG so their use is not considered a reasonable alternative for increasing daily operational flexibility. Summary of Dworkshak Dam and Operations

A brief description of the Army Corps of Engineers' Dworshak Dam is provided here as a comparison to Grand Coulee Dam. Dworshak was selected for this comparison because the reservoir behind Dworshak Dam exhibits strong thermal stratification that allows successful operation of Dworshak Dam for reducing Snake River temperatures.

Dworshak Dam on the North Fork Clearwater River is 1.9 miles upstream of the mainstem Clearwater River. The concrete gravity dam is 717 feet tall (632 feet effective hydraulic height), with a crest length of 3,287 feet and a total storage capacity of 3,468,000 acre-feet of which 2 million acre-feet are used for power generation and FRM (USACE, 2016).

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[16] The 230KV system is the high-voltage transmission from the Left and Right powerhouses. Voltage collapse is a system instability involving many power system components, typically associated with power demand of load not being met due to shortage in power production and transmission.

During summer months, typically July through August, Dworshak Reservoir is drafted to provide water for flow augmentation for the purpose of increasing water velocities in the lower Clearwater and Snake rivers and to moderating river temperatures, improving water quality. The summer temperature moderation and flow augmentation releases from Dworkshak are shaped with the intent to maintain water temperatures at Lower Granite tailrace[17] at or below 20°C (68°F). Dworshak releases are generally sufficient to provide effective water temperature management in the Lower Granite tailrace, but these efforts can be overwhelmed by extremely hot weather or high discharges of warm water from Hells Canyon Dam (on the Snake River). The amount of cold water available from Dworshak Dam for flow augmentation is approximately 1.2 MAF (BPA et al., 2017). Dworshak Dam's penstock intakes are equipped with adjustable gates for selective withdrawal of water between full pool (1,600 ft) and minimum pool (1,445 ft) elevations (USACE 2016). The purpose of the selective withdrawal is to discharge water at a temperature suitable for fish production at the downstream Dworshak National Fish Hatchery and for providing cold water releases during flow augmentation, often the water released for cooling the Snake River is too cold for the hatchery.

2.3 Temperature Regimes and Stratification

In an effort to better understand the thermal regime of Lake Roosevelt, Reclamation has collected routine measurements of the reservoir thermal profile near the dam since 2000. Additionally, Reclamation has developed a two-dimensional[18] (longitudinal-vertical) water quality model to better understand Grand Coulee operations and their effects on Columbia River temperatures and total dissolved gas (TDG). Ex. 5 Deliberative Process (DP)

Ex. 5 Deliberative Process (DP)

2.3.1 Temperatures above and below Grand Coulee

As described previously, Grand Coulee Dam is a large structure that influences the flow of the Columbia River. Median temperatures below Grand Coulee Dam generally range from a low of about 3 degrees during the winter to a high of about 19 degrees by the end of summer ([REF _Ref499105678 \h]). Compared to inflow temperatures at the International Boundary, Grand Coulee releases tend to be warmer September through

[17] The water channel, river, downstream of a dam.

[18] [HYPERLINK "http://www.ce.pdx.edu/w2/"], for more information about CE-QUAL-W2, the water quality model developed for Lake Roosevelt.

January, roughly equivalent February through July, and cooler July through August. These patterns are exhibited in [REF _Ref499105794 \h].

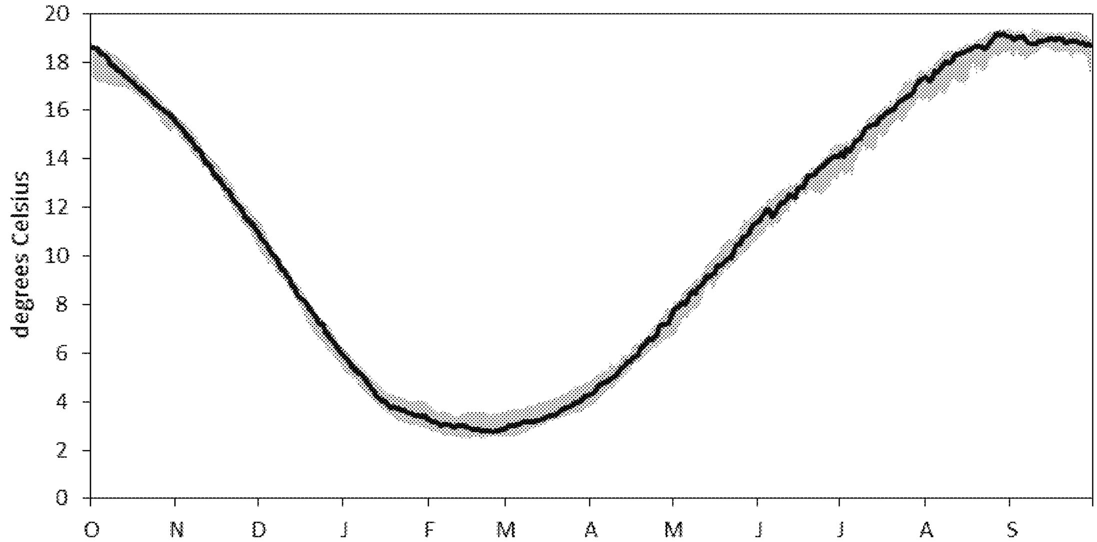

Figure [STYLEREF 1 \s].[SEQ Figure * ARABIC \s 1] Water temperatures measured downstream of Grand Coulee Dam, showing the median, 20%, and 80% exceedance temperatures for water years 2000 through 2015.

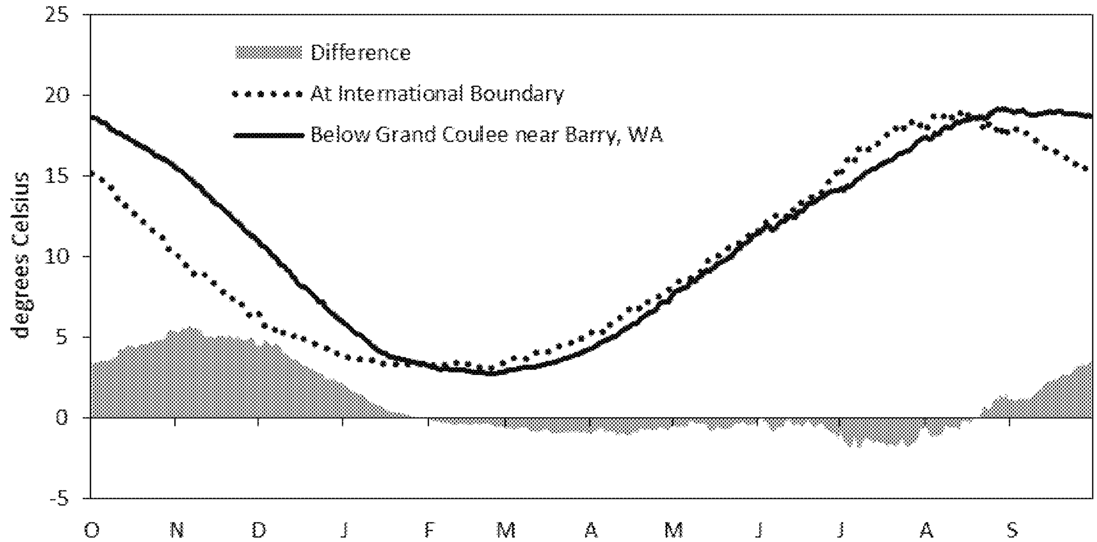

Figure [STYLEREF 1 \s].[SEQ Figure * ARABIC \s 1] Median Columbia River water temperatures measured at the International Boundary and below Grand Coulee Dam near Barry, Washington for water years 2000 through 2015.

2.3.2 Reservoir Stratification

2.3.2.1 Lake Roosevelt

Lake Roosevelt behaves somewhere between a river (riverine) and a lake (lacustrine), the hydrologic reasons for this are further examined in [REF _Ref499105876 \w \h]. During the spring and early-summer, the reservoir warms and weakly stratifies with the development of a warm shallow layer (the epilimnion) in the top 20 to 50 feet (for example [REF _Ref499108014 \h] shows the stratification for water year 2009, see Appendix A for additional water year examples). The penstocks, water intake structures, to the Powerhouse are located below the epilimnion, where the temperature gradient exhibits only a small decrease in temperature with depth. [REF _Ref499106027 \h] illustrates the difference in temperature between the two penstock intakes over time (see [REF _Ref499105979 \h] for additional examples of temperature differences between the two powerhouse intakes). The maximum temperature difference between the penstock elevation of the Left and Right Powerhouse (located at elevation 1,040 feet) and the penstock elevation of the Third Powerhouse (located at elevation 1,140 feet) is normally 1 to 2 degrees Celsius during June and July years ([REF _Ref499106114 \h * MERGEFORMAT]). This temperature difference is insufficient to provide cooler water to the lower Columbia River with the operational constraints at Grand Coulee Dam and the general warming through the mid-Columbia reach that is affected by a series of privately-owned hydropower projects.

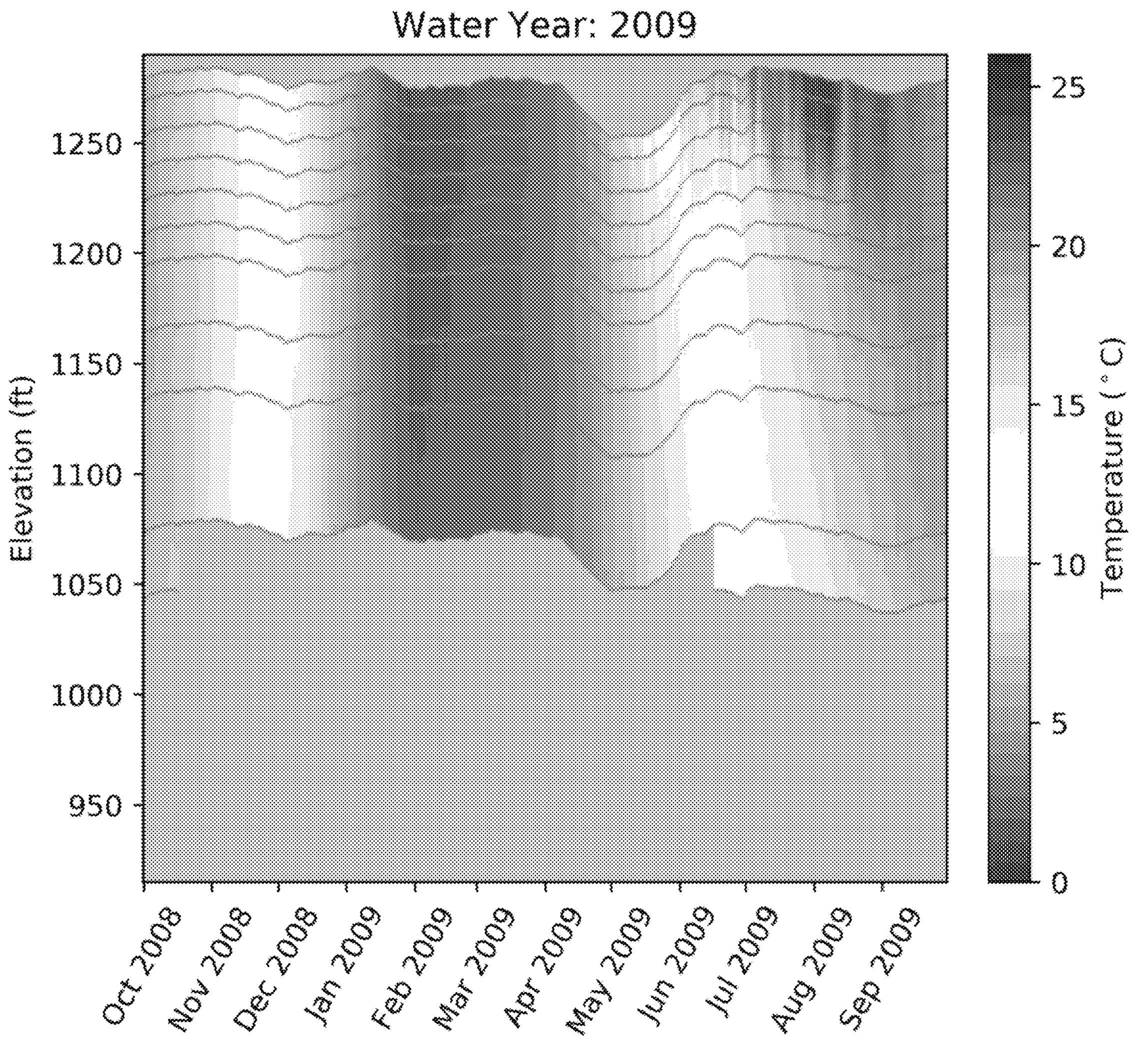

Figure [STYLEREF 1 \s].[SEQ Figure * ARABIC \s 1] Thermal stratification of Lake Roosevelt for water year 2009.

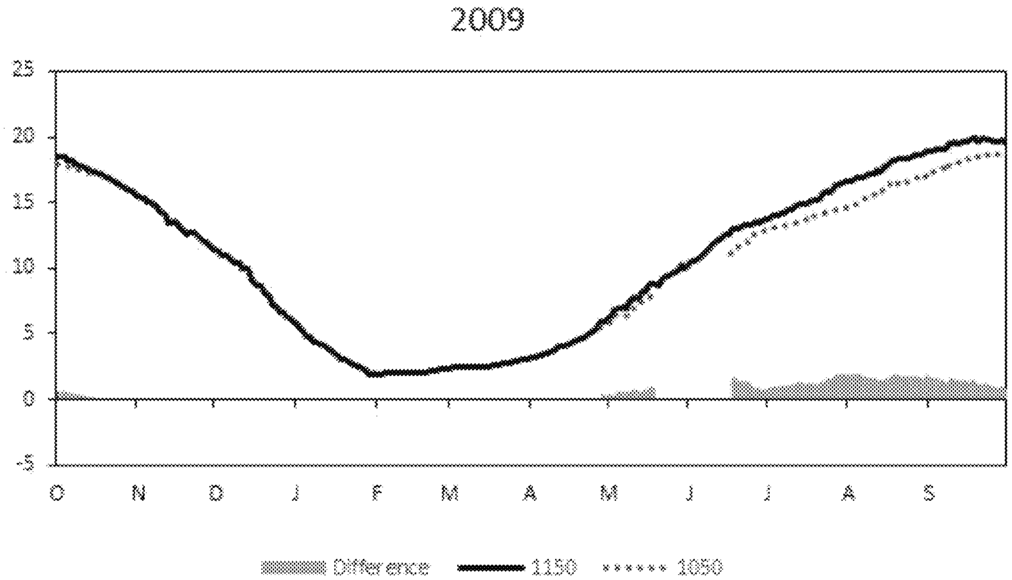

Figure [STYLEREF 1 \s].[SEQ Figure * ARABIC \s 1] Comparison of water temperatures in Lake Roosevelt during water year 2009, at 1150 feet and 1050 feet elevation. These elevations approximate the Power-Plant intakes for the Third Power-Plant (1150 feet), and the Left and Right Power-Plant (1050 feet). Note that data gaps exist due to data collection issues.

Table [STYLEREF 1 \s].[SEQ Table * ARABIC \s 1] Monthly average temperature difference between reservoir temperatures between 1150 feet (approximate elevation of TPP) and 1050 feet (approximate elevation of L&R PP). Data missing in tables reflects data gaps, typically at lower elevation thermistor.

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
2000	0.2	0.3	0.1	0.1	0.0	0.1	0.2	0.1	0.6	1.2	1.8	0.5
2001	0.5	0.5	0.4	0.0	-0.1	0.0	0.3		1.2	1.5	3.5	1.4
2002	0.2	0.5							1.7	2.1	1.8	0.5
2003	0.2	0.4	0.3	0.1	0.1	0.0	0.4	1.1	1.8	1.7	2.1	0.7
2004	0.4	0.3	0.4	0.0		0.0		1.5	1.0	1.5	2.6	0.7
2005	0.4	0.3	0.4	0.0	-0.1	0.0			1.2	1.1	1.3	0.6
2006	0.3							0.3		1.7	1.6	0.4
2007	0.6											
2008	0.4	0.7	0.5	0.1	-0.1	0.0	0.2	0.4	0.4	2.0	1.5	0.8
2009	0.4						0.4	0.7	1.2	1.3	1.8	1.3
2010	0.4							1.1		1.7	1.1	1.1
2011	0.7					0.0	0.1	0.2	0.1	0.7	0.9	1.0
2012	0.2					0.0	0.1	0.2	0.1			
2013	0.2									1.4	1.3	0.7
2014	0.3					0.0	0.2	0.4	0.5	1.1	1.1	0.4
2015	0.3					0.0	0.2	1.2	1.2	0.9	0.3	0.4
2016						0.1	0.5	0.7				
Average	**0.4**	**0.4**	**0.4**	**0.0**	**0.0**	**0.0**	**0.3**	**0.6**	**0.9**	**1.4**	**1.6**	**0.8**
Max	0.7	0.7	0.5	0.1	0.1	0.1	0.5	1.5	1.8	2.1	3.5	1.4

2.3.2.2 Dworshak Reservoir Stratification

In contrast to the Columbia River at Grand Coulee Dam, the thermal conditions of the North Fork Clearwater River at Dworshak Dam are much cooler in the summer ([REF _Ref499108137 \h * MERGEFORMAT], also see [REF _Ref499108235 \h * MERGEFORMAT]). This is due to the cooler inflows to the reservoir and because of the thermal stratification that occurs in Dworshak Reservoir. The water that is released from Dworshak can take advantage of the stratification, and release cooler water from the hypolimnion during mid- to late-summer months, resulting in cool releases well below equilibrium temperature. Temperature differences between the Snake River and Clearwater River at the confluence, near the upstream edge of Lower Granite Reservoir, is typically 10°C or more during July and August (Cook et al. 2006). The volume of water coming in from both the Clearwater and Snake rivers are similar in magnitude, and because of the temperature related density difference between the two rivers during summer flow augmentation periods the water does not mix immediately, so the Snake River, Lower Granite Reservoir as well as the other three reservoirs downstream stratify (Cook et al. 2006).

Because of the large temperature difference at the Clearwater and Snake River confluence the Dworkshak releases (well below 'equilibrium' temperature[19]) has a large impact on the Clearwater and lower Snake River system. Releases from Dworshak warm quickly, typically by 4.5°C when the Clearwater River flows into the Snake River at the upper end of Lower Granite Reservoir (Cook et al. 2006).

[19] Equilibrium temperature is defined as the point when two objects in contact, in this case the atmosphere and river, and the net exchange of energy is zero.

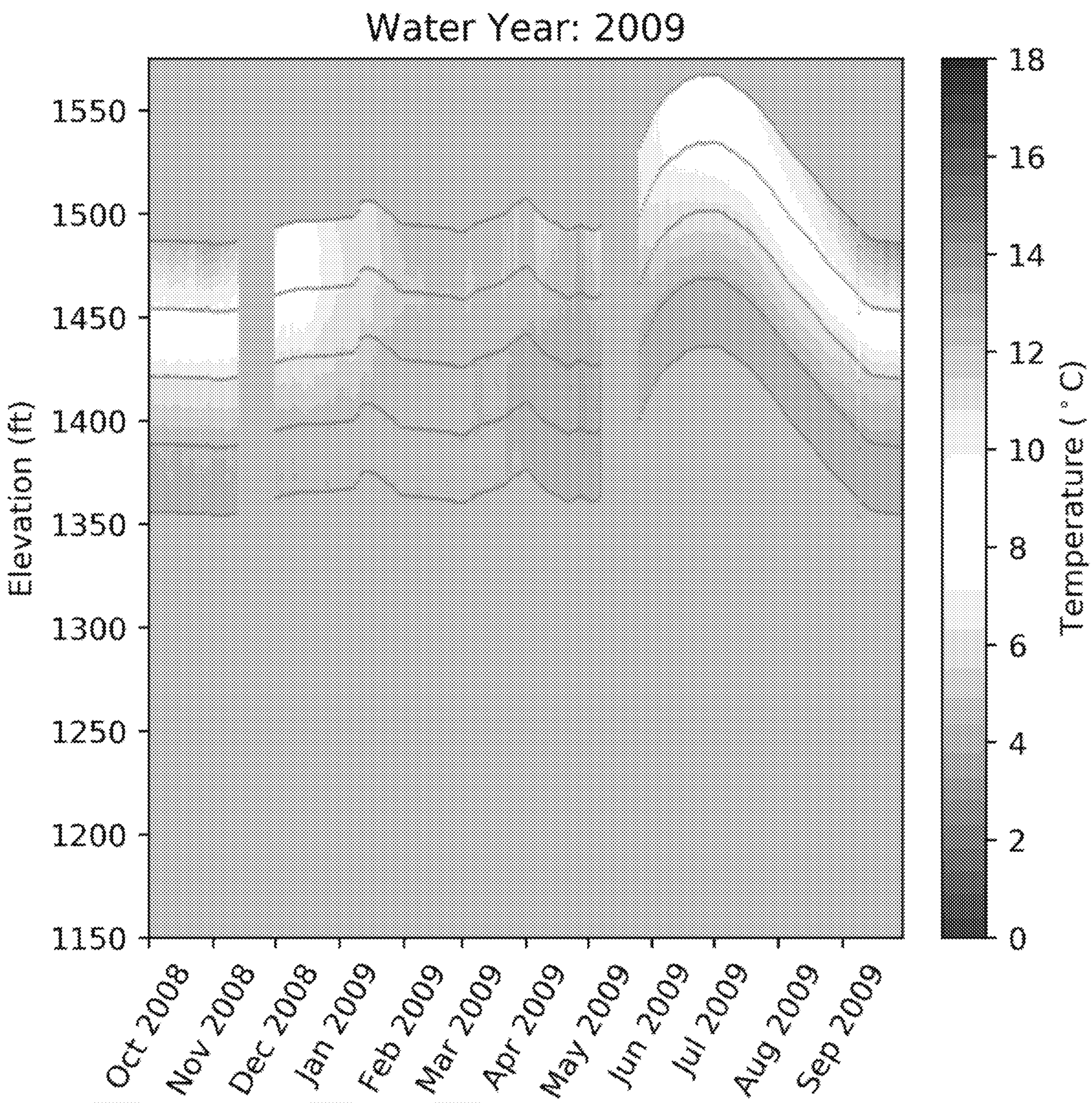

Figure [STYLEREF 1 \s].[SEQ Figure * ARABIC \s 1] Thermal stratification of Dworshak Reservoir for water year 2009, the temperature scale has been adjusted to allow visualization of the stratification. Appendix B includes thermal stratification plots of Dworshak Reservoir for water years 2006 to 2015. The color scale ranges from 0 to 18ºC.

2.3.3 Reservoir Retention Time

The retention time (RT) of a reservoir is the average time a water molecule will spend in that reservoir. RT is a theoretical value calculated as the ratio of reservoir volume to average daily flow (either inflow or outflow). The RT in a reservoir or lake is important because it influences a number of lake and reservoir behaviors including stratification (increasing with increasing retention time) and retention of nutrients (Straskraba 1999). When RT is short the entire reservoir could become a riverine zone, and when the RT is long it can be a more lacustrine (lake) zone (1999). The retention time influences both the longitudinal and vertical patterns observed in a reservoir and is the most useful variable for prediction of stratification (Straskraba 1999).

The heat gain by a reservoir can typically be divided into two components, the advective flow of water and energy (temperature) from upstream and the net gain of energy (temperature) from solar radiation on the reservoir. The RT controls the significance of the advective source of heat, with shorter RT corresponding to increased influence of advective heat gain.

2.3.3.1 Grand Coulee and Lake Roosevelt

Despite the fact that Lake Roosevelt is a rather large storage project, the reservoir does not exhibit prominent stratified conditions like other large storage reservoirs ([REF _Ref499108652 \h]). This can be explained in part by Lake Roosevelt's relatively short retention time ([REF _Ref499108508 \h]).

Inflows into Lake Roosevelt are generally large enough that the entire capacity (9.4 MAF) can be refilled seven or eight times each year (average annual flow at Grand Coulee Dam is 77 MAF, or about 106,000 cfs). In dry years (for example 2001), there is generally enough flow to completely refill the reservoir approximately six times, while in wet years (such as 1997), there is generally enough water for this to occur 11 times.

Using the ratio of storage volume to flow rate as an indicator of average residence time in Lake Roosevelt, the monthly average residence time varies from 11 days in May to 38 days in October.

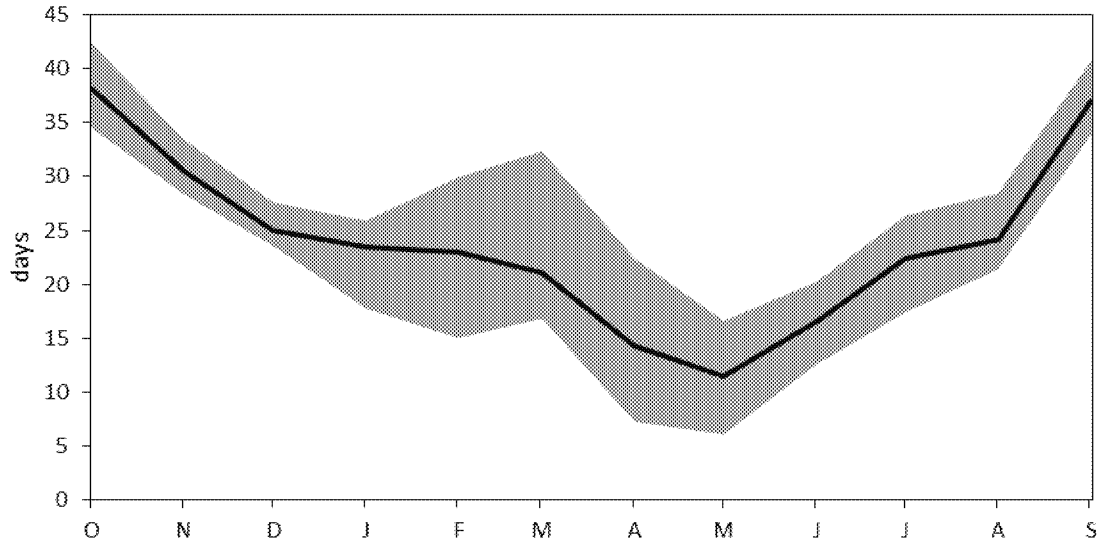

Figure [STYLEREF 1 \s].[SEQ Figure * ARABIC \s 1] Average monthly residence time of Lake Roosevelt presented in terms of the ratio between storage volume and flow rate for the 2000-2015 water years. Gray bounds represent the 20th- and 80th-percentile values.

2.3.3.2 Dworshak Dam and Reservoir

Dworshak Reservoir experiences strong thermal stratification. On average inflows into Dworshak Reservoir can fill the entire capacity (~3.5 MAF) once each year (average annual flow at Dworshak Dam is 3.9 MAF, or about 5,300 cfs). The monthly average residence times (i.e. storage volumes divided by flow rates) range from 87 days in August to 348 days in December. [REF _Ref499108749 \h] and [REF _Ref499108758 \h] compare the RT of Dworshak Reservoir to Lake Roosevelt.

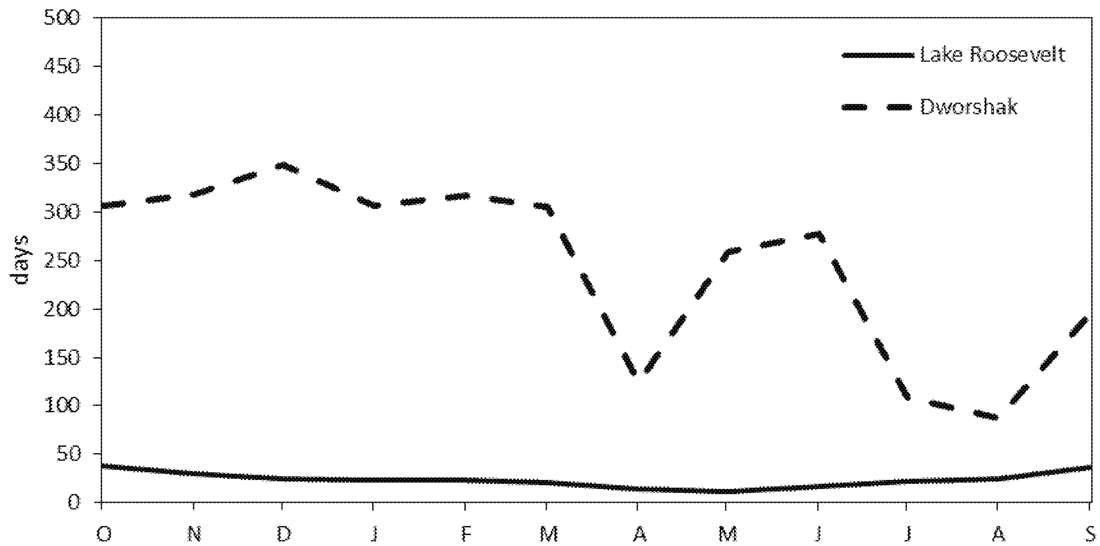

Figure [STYLEREF 1 \s].[SEQ Figure * ARABIC \s 1] Monthly average residence time of Lake Roosevelt and Dworshak Reservoir in terms of the ratio between storage volume and flow rate for the 2000-2015 (2003-2015 for Dworshak) water years.

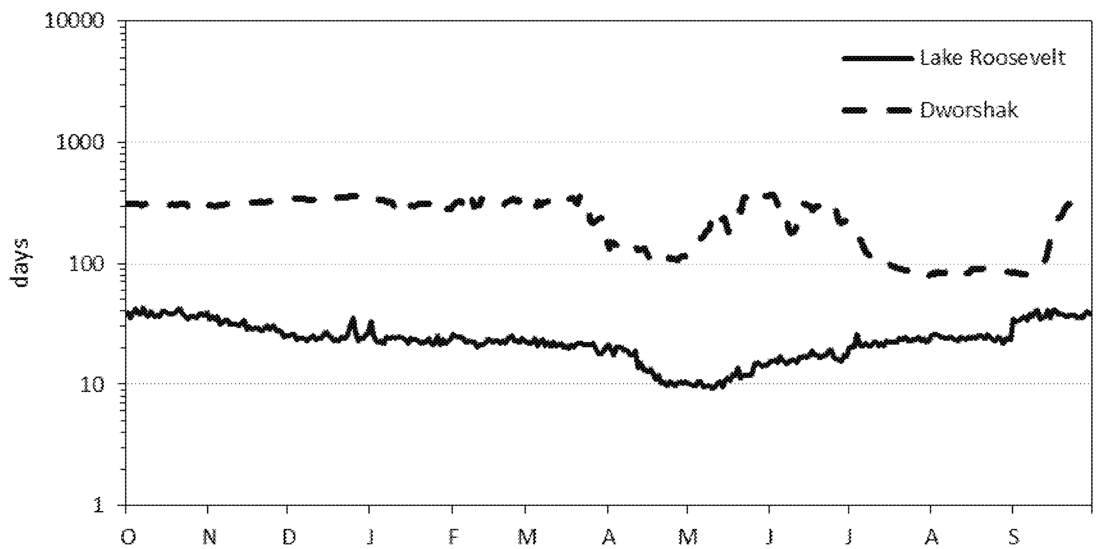

Figure [STYLEREF 1 \s].[SEQ Figure * ARABIC \s 1] Daily average residence time of Lake Roosevelt and Dworshak Reservoir in terms of the ratio between storage volume and flow rate for the 2000-2015 (2003-2015 for Dworshak) water years.

2.3.4 2015

NOAA Fisheries (2016) documents in their Adult Sockeye Salmon Report that migration conditions during June and July of 2015 were detrimental to sockeye salmon such that sockeye salmon, sustained heavy losses in the Columbia and Snake Rivers and tributaries. ESA-listed Snake River sockeye salmon were especially affected in the mainstem migration corridor, with losses exceeding 95% between Bonneville and Lower Granite dams (NOAA 2016).[20] The cause of high losses has been linked to river conditions, including high river temperatures during migration. During the summer of 2015, low flow conditions ([REF _Ref499109371 \h] and [REF _Ref499109297 \h]) combined with higher than normal air temperatures (for example two Hydromet stations in Washington measured several warm events well above average, [REF _Ref499109422 \h]) resulted in high stream temperatures in the Columbia and Snake Rivers, and their tributaries. The Columbia River volumetric runoff at Grand Coulee for the spring-summer period (April-August) was well below the 30-year average at 42 MAF or 74% of average. The lower Columbia River and Snake River runoff volumes were even lower in comparison to the 30-year average at 67% (58 MAF) and 54% (11.5 MAF) respectively.

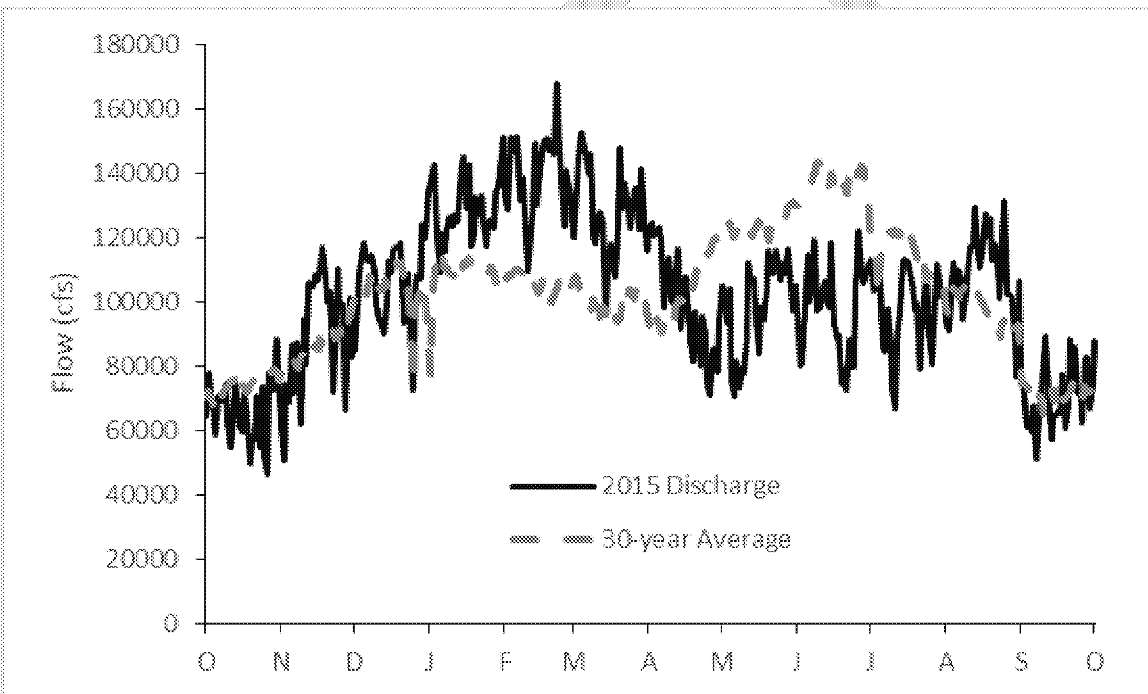

Figure [STYLEREF 1 \s].[SEQ Figure * ARABIC \s 1] Grand Coulee Dam outflows for water year 2015 vs. 30-year average.

In 2015, Grand Coulee outflows during June and early July were 1 to 2 degrees cooler than Columbia River temperatures upstream at the international boundary ([REF _Ref499109525 \h]), this is a pattern that occurs each year where Grand Coulee Dam

[20] Other species of salmon and steelhead typically migrate outside of this time period both as juvenile and adults and were not substantially impacted.

releases water that is cooler than inflow during spring and summer and warmer during fall and winter.

Inflow temperatures to Lake Roosevelt, as measured at the international boundary, and outflow temperatures from Lake Roosevelt were slightly higher than normal (see comparison to median in [REF _Ref499109525 \h]). During June and July, the period when most adult sockeye migrate in the Columbia and Snake Rivers, river temperatures downstream of Grand Coulee Dam were 13 to 19 ºC in 2015, on average the temperatures during this period are 11 to 17 ºC. Water temperatures increased by about 3˚C such that the daily average temperatures downstream of Priest Rapids Dam (near Pasco, WA) were 16 to 21 ºC (average daily temperatures are typically between 14 to 20 ºC for this period, [REF _Ref499109589 \h]).

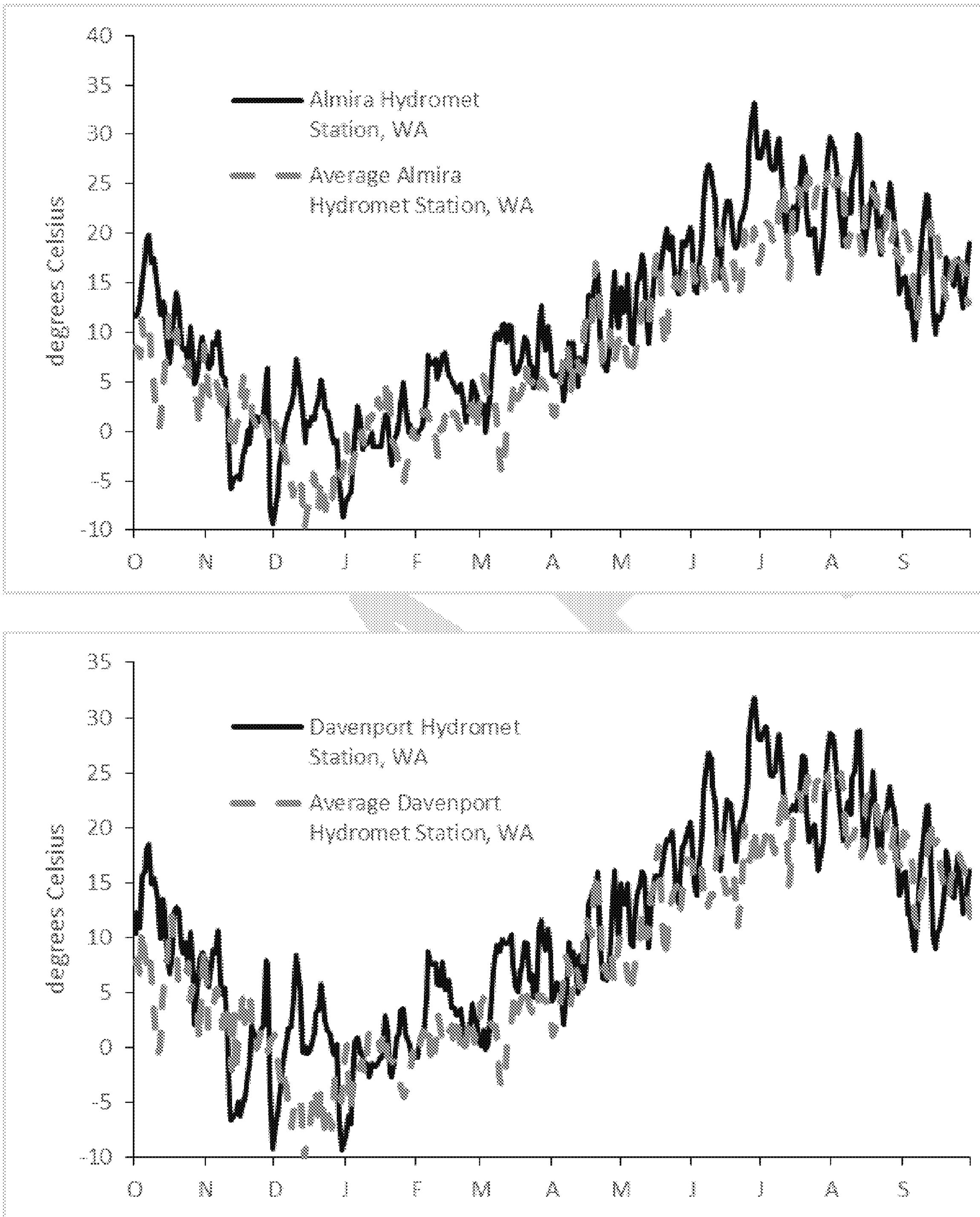

Figure [STYLEREF 1 \s].[SEQ Figure * ARABIC \s 1] Air temperatures at select Hydromet stations (Almira – top, Davenport – bottom) in Washington to characterize weather conditions during the 2015 water year (solid black line) compared to average conditions (dashed grey line).

Daily Snake River temperatures as measured at Lower Granite Dam during the June-July period varied between 16 and 21°C (typically average daily temperatures are between 12 and 19 °C for this period, [REF _Ref499109667 \h]), and the Lower Columbia River at The Dalles Dam varied between 17 and 24°C (typically average daily temperatures are between 14 to 21 °C for this period, [REF _Ref499109765 \h]).

The stratification in Lake Roosevelt followed a similar pattern as most years ([REF _Ref499109860 \h]), with higher temperatures than Dworshak ([REF _Ref499109877 \h]) and little stratification between the powerhouse intake elevations ([REF _Ref499106114 \h * MERGEFORMAT])

In summary, the combination of high air temperatures and low flows resulted in above normal river temperatures in the Snake and Columbia Rivers. As NOAA (2016) documented the temperatures in tributaries and upstream of storage projects were also well above normal. Inflow and outflow temperature at Grand Coulee were higher than normal during the June-July period but outflow temperatures were cooler than inflow temperatures. Similar to conditions in the Snake River, the Columbia River warms as it moves downstream the Middle-Columbia reach, with an increase in temperature of several degrees between Grand Coulee Dam (river mile 597) and McNary (river mile 292) over roughly 300 miles.

Table [STYLEREF 1 \s].[SEQ Table * ARABIC \s 1] Runoff volumes by month for the Columbia River at Grand Coulee Dam, Snake River at Lower Granite Dam, and the Columbia River at The Dalles Dam (NWRFC, 2015).

Water Year 2015	October	November	December	January	February	March	April	May	June	July	August	September	April-August
Columbia River at Grand Coulee Dam (KAF)	3191	3878	3578	3102	5770	7123	6923	12351	12550	6146	4135	4024	42105
% of average	115	134	146	126	237	193	97	80	72	56	72	120	74%
Snake River at Lower Granite Dam (KAF)	1256	1501	1958	2087	3188	3013	2919	4220	2350	1105	872	931	11466
% of average	88	93	111	106	141	90	64	61	39	48	70	78	54%
Columbia River at The Dalles Dam (KAF)	4963	6363	7150	7185	11348	11959	11504	18333	15807	7552	5211	5245	58407
% of average	98	113	128	120	178	131	83	72	60	52	68	101	67%

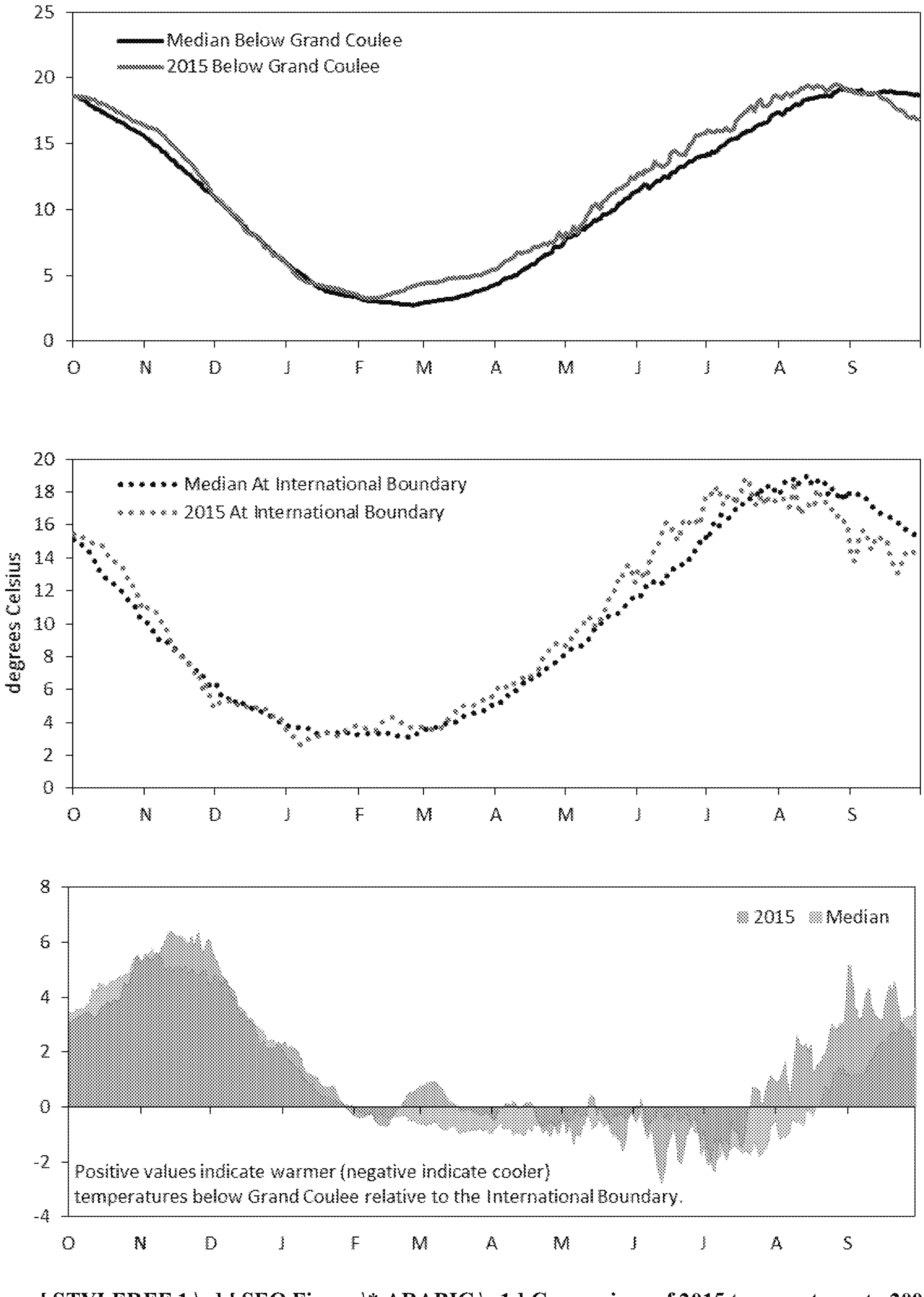

Figure [STYLEREF 1 \s].[SEQ Figure * ARABIC \s 1] Comparison of 2015 temperatures to 2000-2015 median temperatures on the Columbia River below Grand Coulee Dam near Barry, WA (top), at the International Boundary (middle), and in terms of temperature difference between these two locations (bottom).

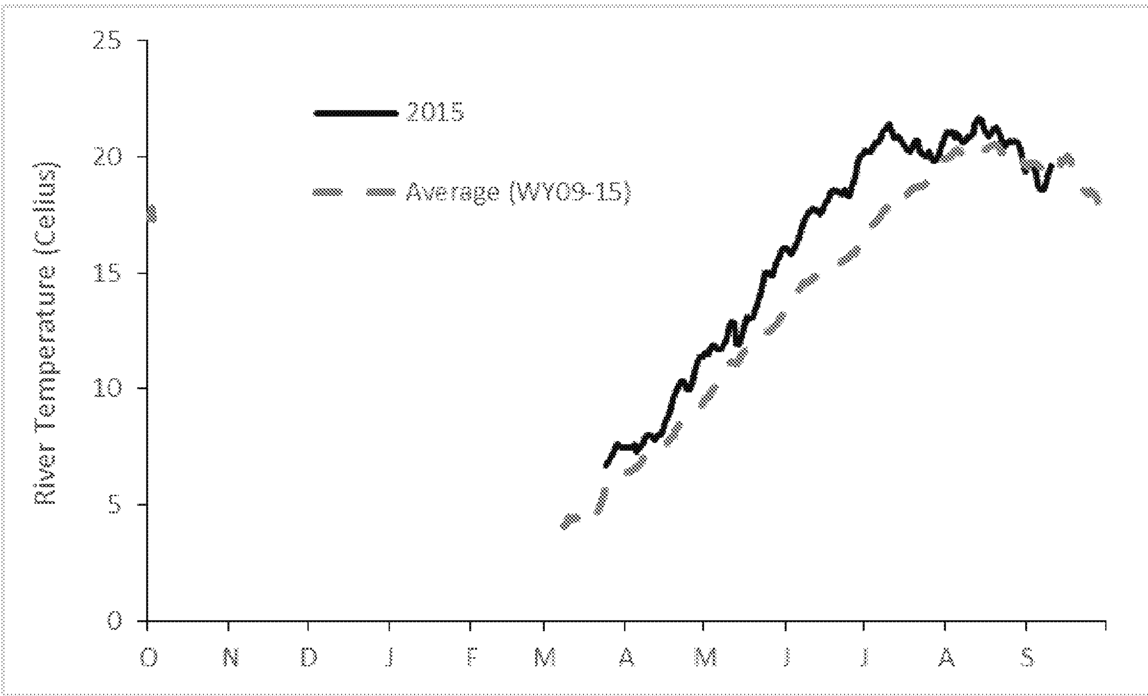

Figure [STYLEREF 1 \s].[SEQ Figure * ARABIC \s 1] Columbia River temperatures downstream of Priest Rapids Dam, near Pasco, WA, source: USGS 12514400 COLUMBIA RIVER BELOW HWY 395 BRIDGE AT PASCO, WA.

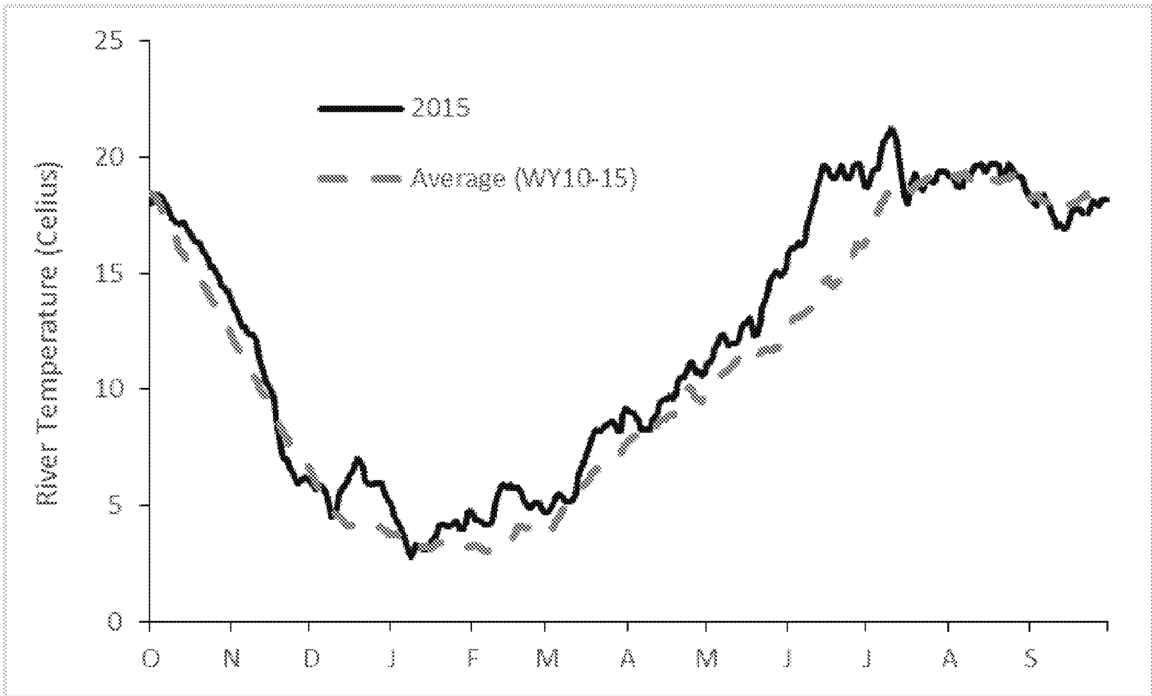

Figure [STYLEREF 1 \s].[SEQ Figure * ARABIC \s 1] Snake River temperatures downstream of Lower Granite Dam, source: USGS 13343595 SNAKE RIVER (RIGHT BANK) BL LOWER GRANITE DAM, WA.

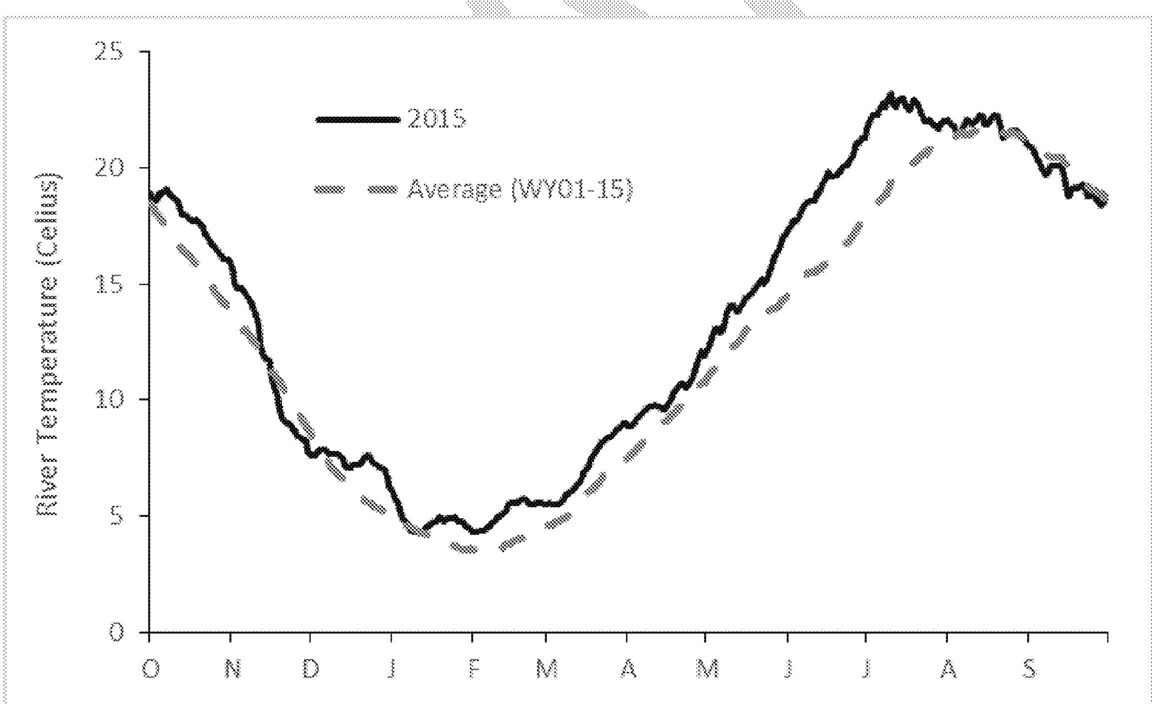

Figure [STYLEREF 1 \s].[SEQ Figure * ARABIC \s 1] Columbia River temperatures downstream of The Dalles Dam, source: USGS 14105700 COLUMBIA RIVER AT THE DALLES, OR.

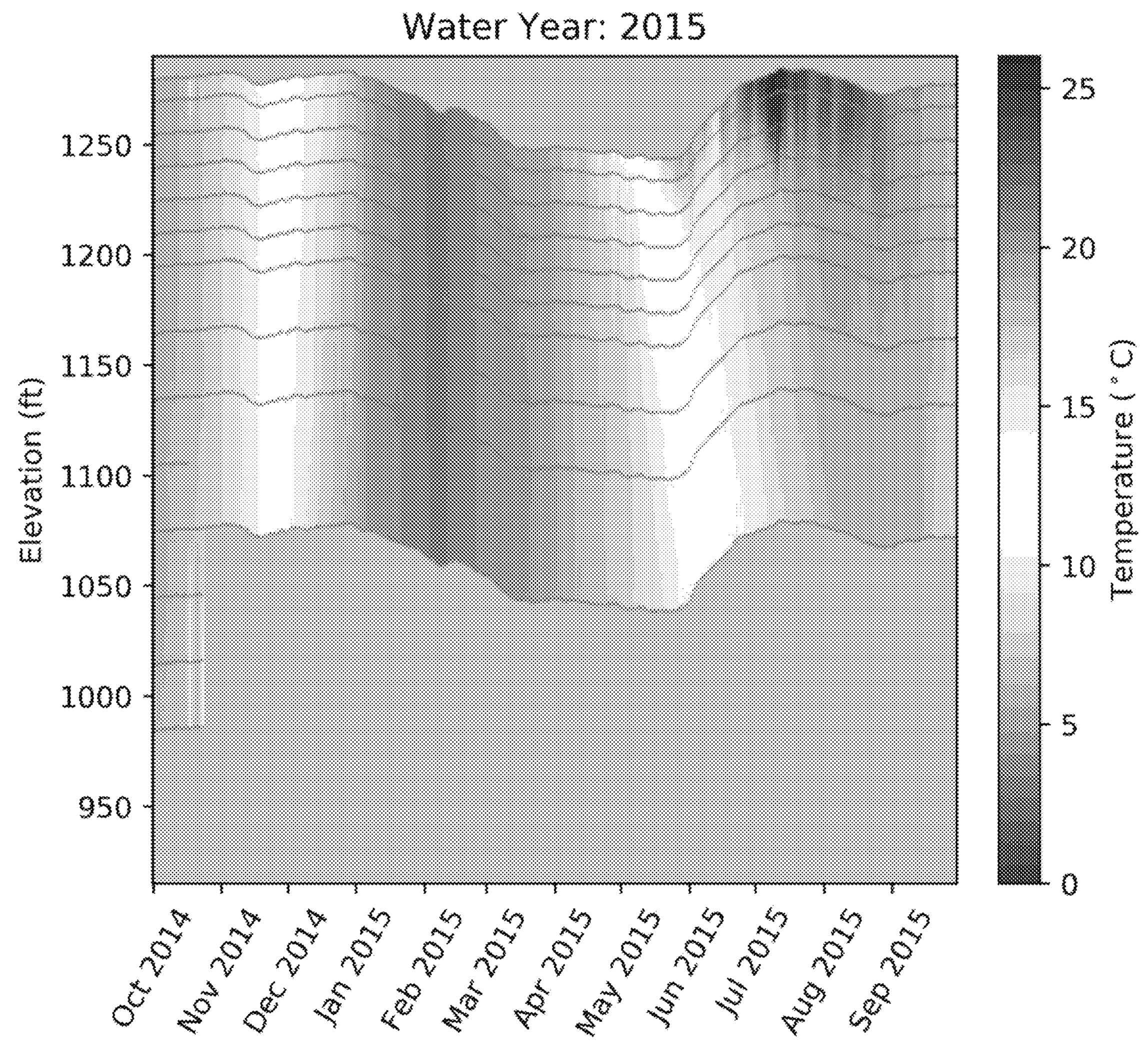

Figure [STYLEREF 1 \s].[SEQ Figure * ARABIC \s 1] Lake Roosevelt temperature profile for water year 2015. Grey background is missing data or above the water surface elevation.

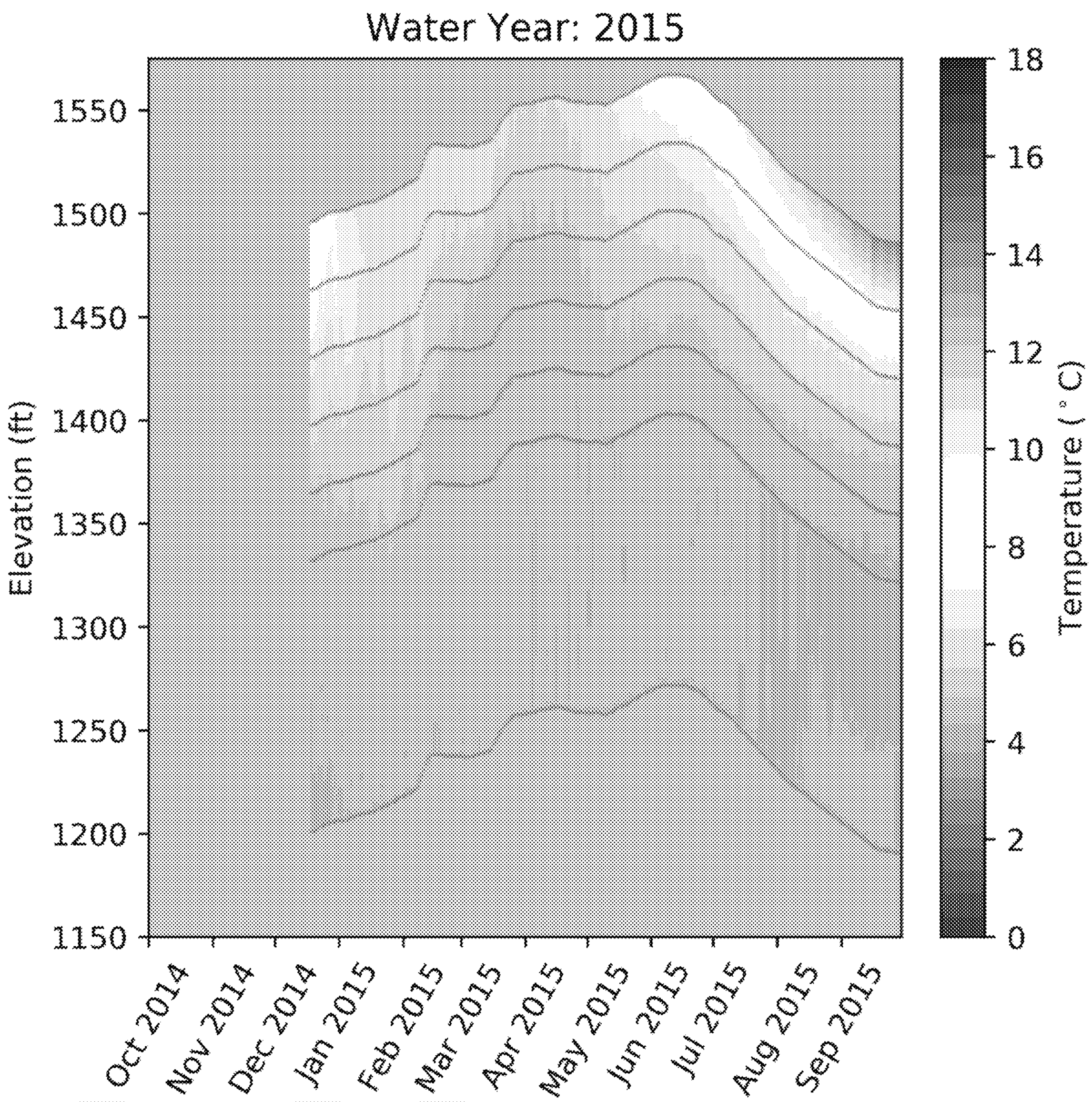

Figure [STYLEREF 1 \s].[SEQ Figure * ARABIC \s 1] Dworshak Reservoir temperature profile for water year 2015. Grey background is missing data or above the water surface elevation.

3 CONCLUSION

Warm water events that affect anadromous fish species, such as the summer of 2015, highlight the need for fish and water managers to investigate potential actions that would reduce water temperatures and reduce risk to migrating fish. Some storage reservoirs impound rivers and thermally behave similar to lakes. A good example of this type of reservoir is Dworshak Reservoir on the Clearwater River in Idaho. Although Grand Coulee Dam is a large storage reservoir, the relatively large volume of flow through the reservoir, with respect to storage capacity, results in a reservoir that does not exhibit strong thermal stratification. The reservoir most often referenced for the perceived potential of Grand Coulee Dam to operate for temperature mitigation is Dworshak Dam, but there are key differences. Ex. 5 Deliberative Process (DP)

Ex. 5 Deliberative Process (DP)

Ex. 5 Deliberative Process (DP)

1. Inflow and outflow temperatures at Grand Coulee Dam - Compared to inflow temperatures at the International Boundary, Grand Coulee releases tend to be warmer September through January, slightly cooler in February through July, and cooler July through August. In 2015 Grand Coulee releases were warmer from October through January, roughly equivalent February through April, slightly cooler March through July then warmer August through September.

2. Weak Stratification – Grand Coulee dam has short retention time and very little stratification (especially in comparison with Dworshak). Retention times in Lake Roosevelt range from 11 days on average in May (shortest) to 38 days on average in October (longest). Much stronger stratification, and temperatures well below equilibrium temperatures, would be necessary for meaningful thermal mitigation for the lower Columbia River from Grand Coulee operations.

3. Operational Flexibility - There is limited flexibility to change operations between the Grand Coulee powerhouses (i.e. release water from different depths in the reservoir). The Left and Right powerhouses release from 100 feet deeper than the Third Powerhouse. The units in the Left and Right are operated continuously while the units in the Third are cycled on and off for peaking operations. Ex. 5 Deliberative Process (DP)

Ex. 5 Deliberative Process (DP)

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[21] Equilibrium temperature is defined as the point when two objects in contact, in this case the atmosphere and river, and the next exchange of energy is zero.

3.1 Next Steps

On July 6, 2016 the U.S. District Court in Oregon issued its remand order for the NOAA BiOp litigation. The ruling found current NEPA coverage to be inadequate and ordered the Action Agencies (U.S. Army Corps of Engineers, Bureau of Reclamation, and Bonneville Power Administration) to conduct comprehensive NEPA on the FCRPS operations. The resulting Columbia River System Operations (CRSO) Environmental Impact Statement (EIS) is mandated to be complete by 2021.

Ex. 5 Deliberative Process (DP)

4 REFERENCES

Parenthetical Reference	Bibliographic Citation
BPA, 2015	https://www.bpa.gov/news/newsroom/Pages/Millions-of-Columbia-River-salmon-return-home-in-2015.aspx
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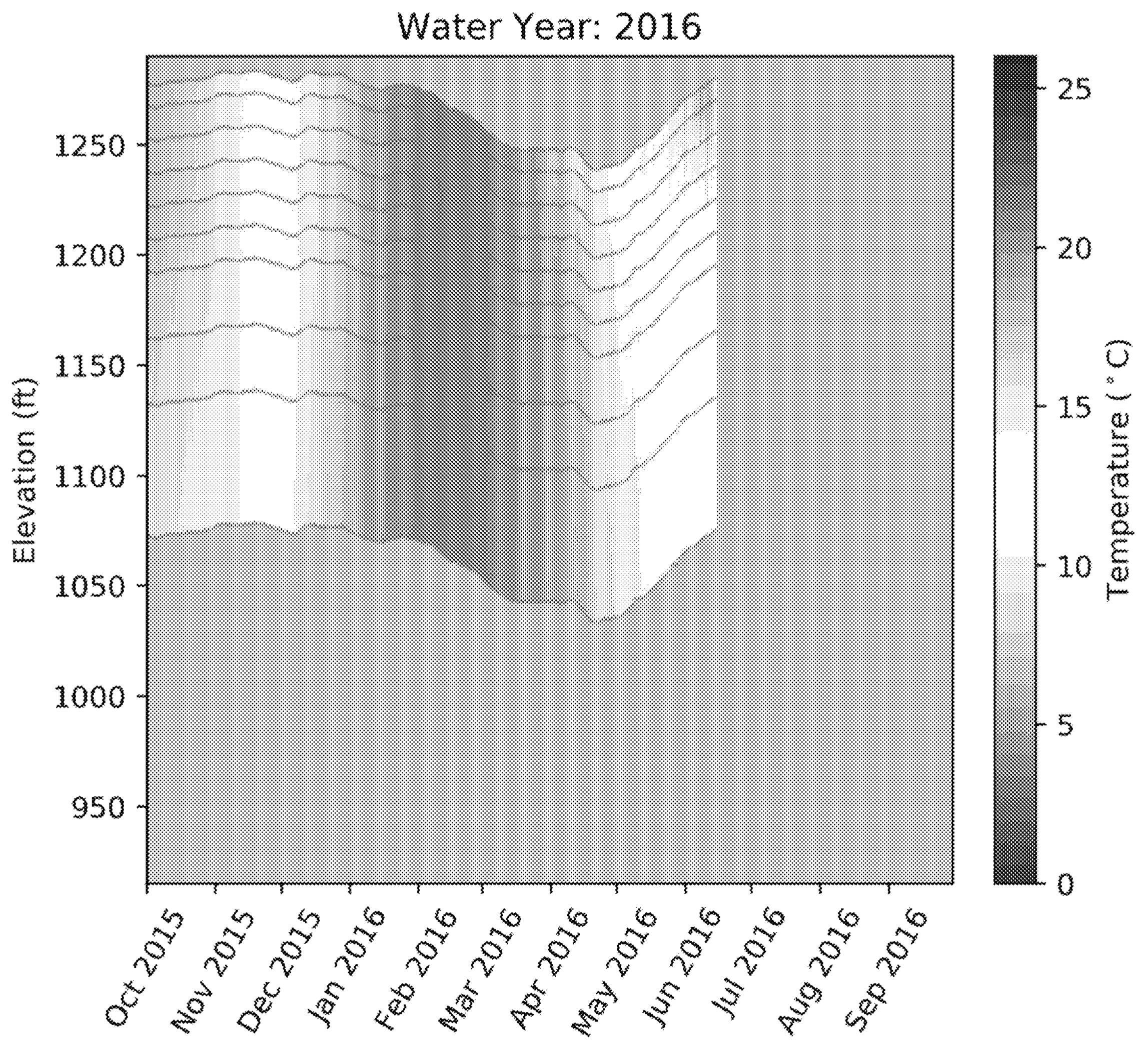
U.S. Army Corps of Engineers (USACE), 2016	USACE, 2016. http://www.nww.usace.army.mil/Locations/District-Locks-and-Dams/Dworshak-Dam-and-Reservoir/. Walla Walla District.
Vermeyen, 2000	Vermeyen, T. (March 2000). Review of Past Studies and Data Related to Temperature Management Options for the Columbia River below Grand Coulee Dam, Washington. Bureau of Reclamation, Technical Service Center, Denver, CO.

5 APPENDIX A: GRAND COULEE DAM AND FRANKLIN D. ROOSEVELT RESERVOIR THERMAL STRATIFICATION

The following figures display the pool temperature data for Lake Roosevelt for water years 2000 to 2016, the color scale represents 0 to 18°C, grey is missing data. The data is available upon request. The grey lines depict the pool elevation correct sensor elevation, values between the sensors are interpolated.


Water Year: 2016
Elevation (ft)
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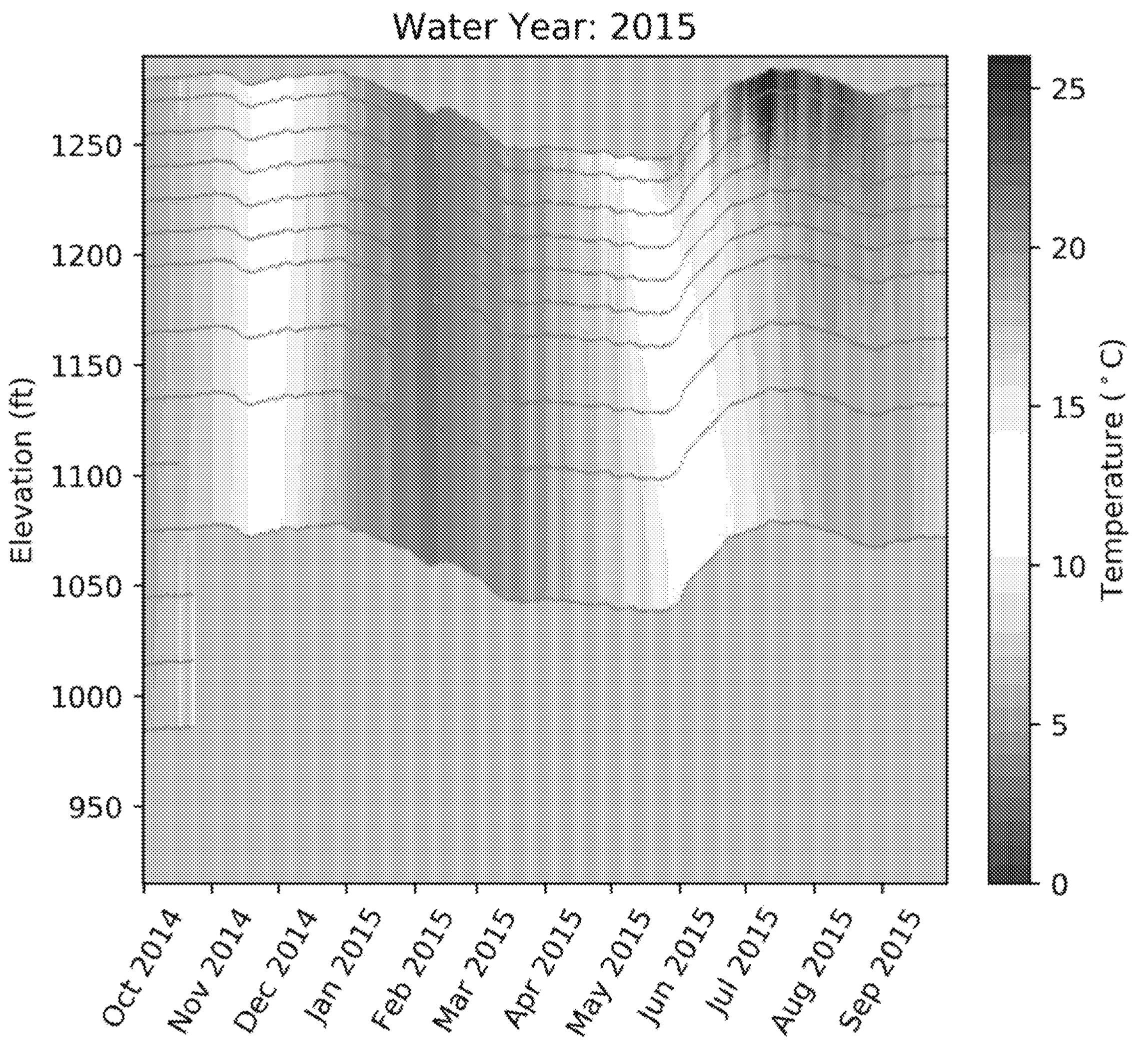
1200
1150
1100
1050
1000
950
Oct 2015
Nov 2015
Dec 2015
Jan 2016
Feb 2016
Mar 2016
Apr 2016
May 2016
Jun 2016
Jul 2016
Aug 2016
Sep 2016
Temperature (°C)
25
20
15
10
5
0



Water Year: 2015
Elevation (ft)
1250
1200
1150
1100
1050
1000
950
Oct 2014
Nov 2014
Dec 2014
Jan 2015
Feb 2015
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Apr 2015
May 2015
Jun 2015
Jul 2015
Aug 2015
Sep 2015
Temperature (°C)
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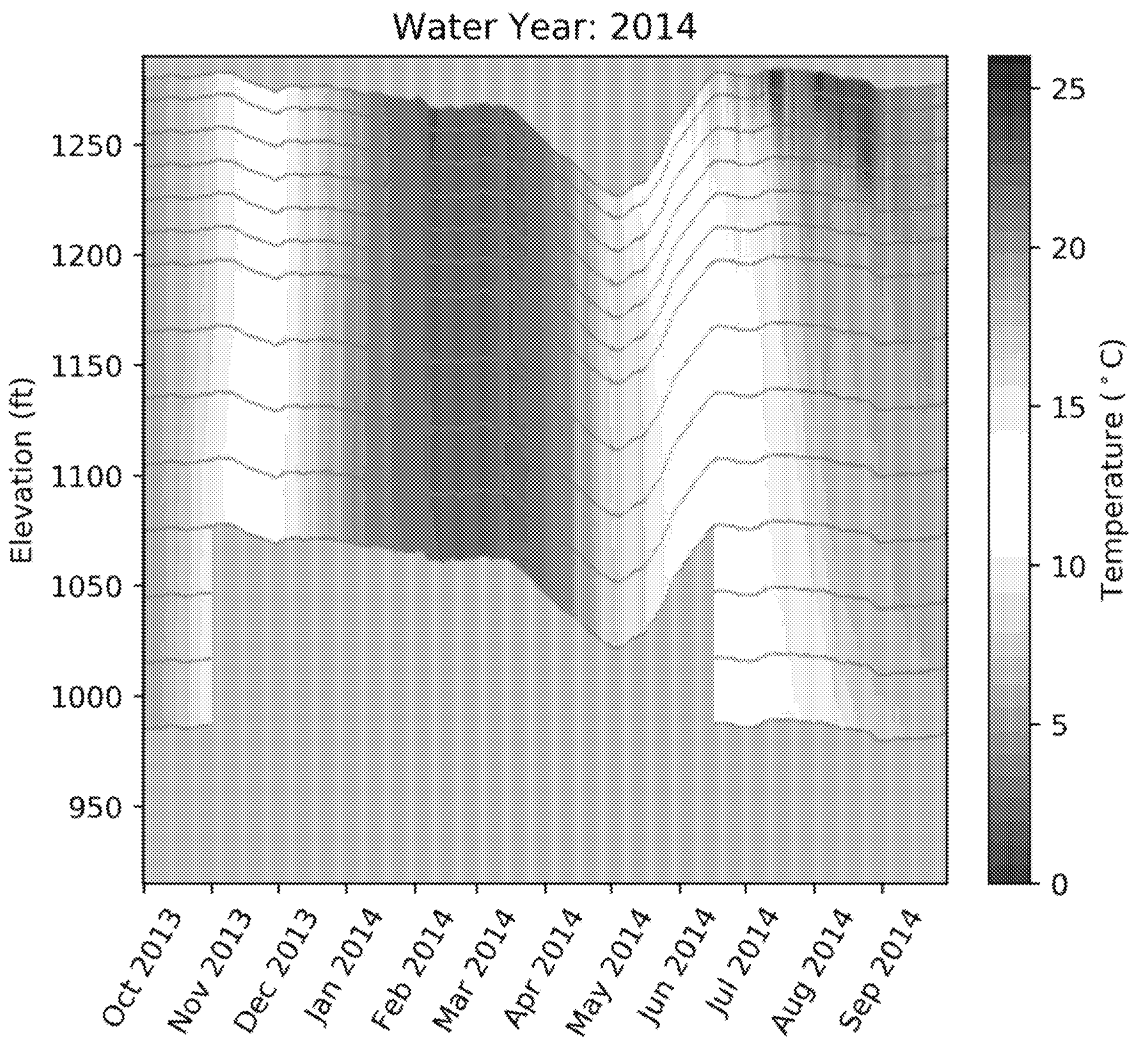
20
15
10
5
0


Water Year: 2014
Elevation (ft)
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1200
1150
1100
1050
1000
950
Oct 2013
Nov 2013
Dec 2013
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Feb 2014
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Jul 2014
Aug 2014
Sep 2014
Temperature (°C)
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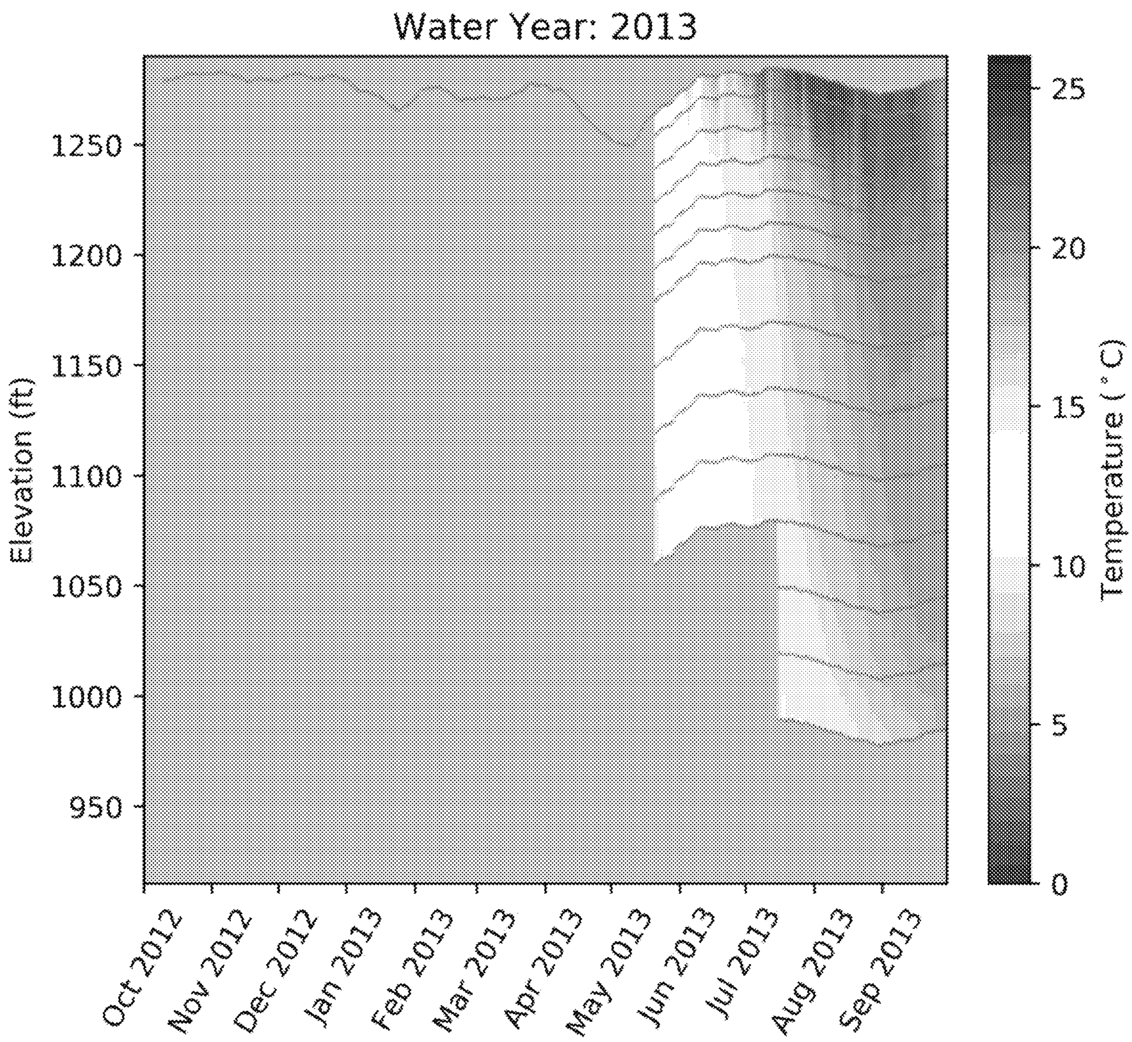
20
15
10
5
0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Elevation (ft)
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1200
1150
1100
1050
1000
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Oct 2012
Nov 2012
Dec 2012
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Feb 2013
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Temperature (°C)
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20
15
10
5
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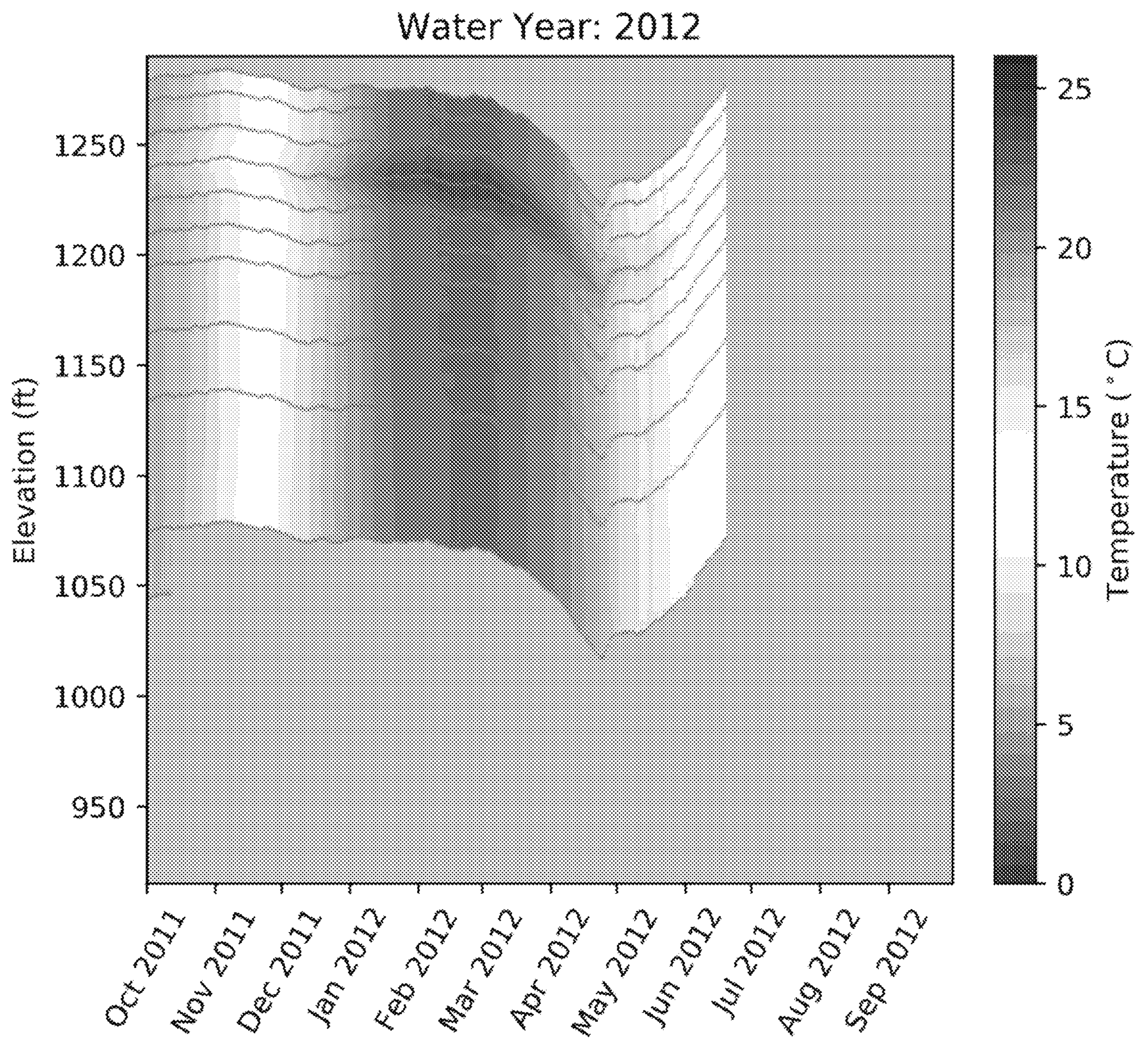

Water Year: 2012
Elevation (ft)
1250
1200
1150
1100
1050
1000
950
Oct 2011
Nov 2011
Dec 2011
Jan 2012
Feb 2012
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Temperature (°C)
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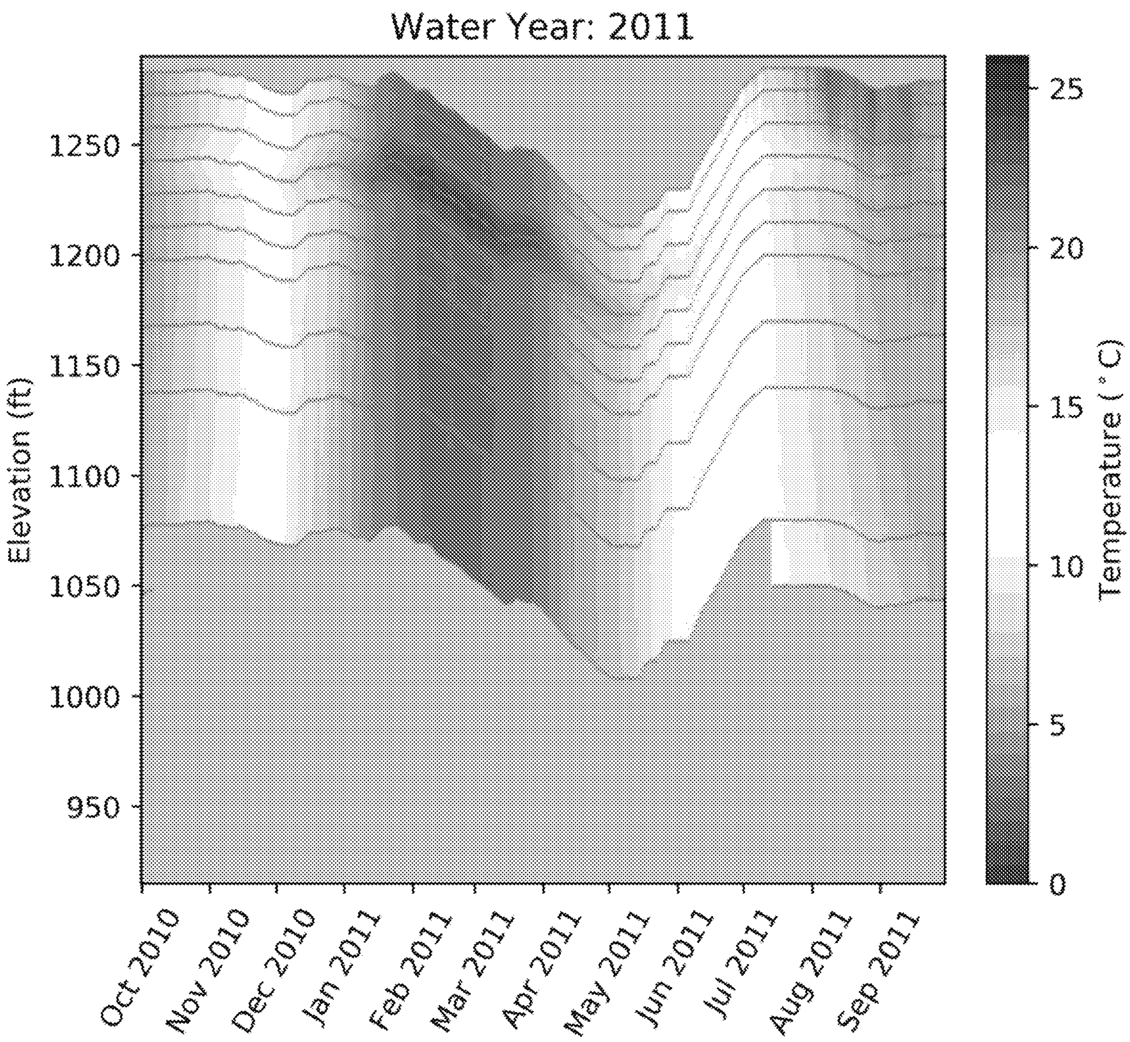
20
15
10
5
0


Water Year: 2011
Elevation (ft)
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1200
1150
1100
1050
1000
950
Oct 2010
Nov 2010
Dec 2010
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20
15
10
5
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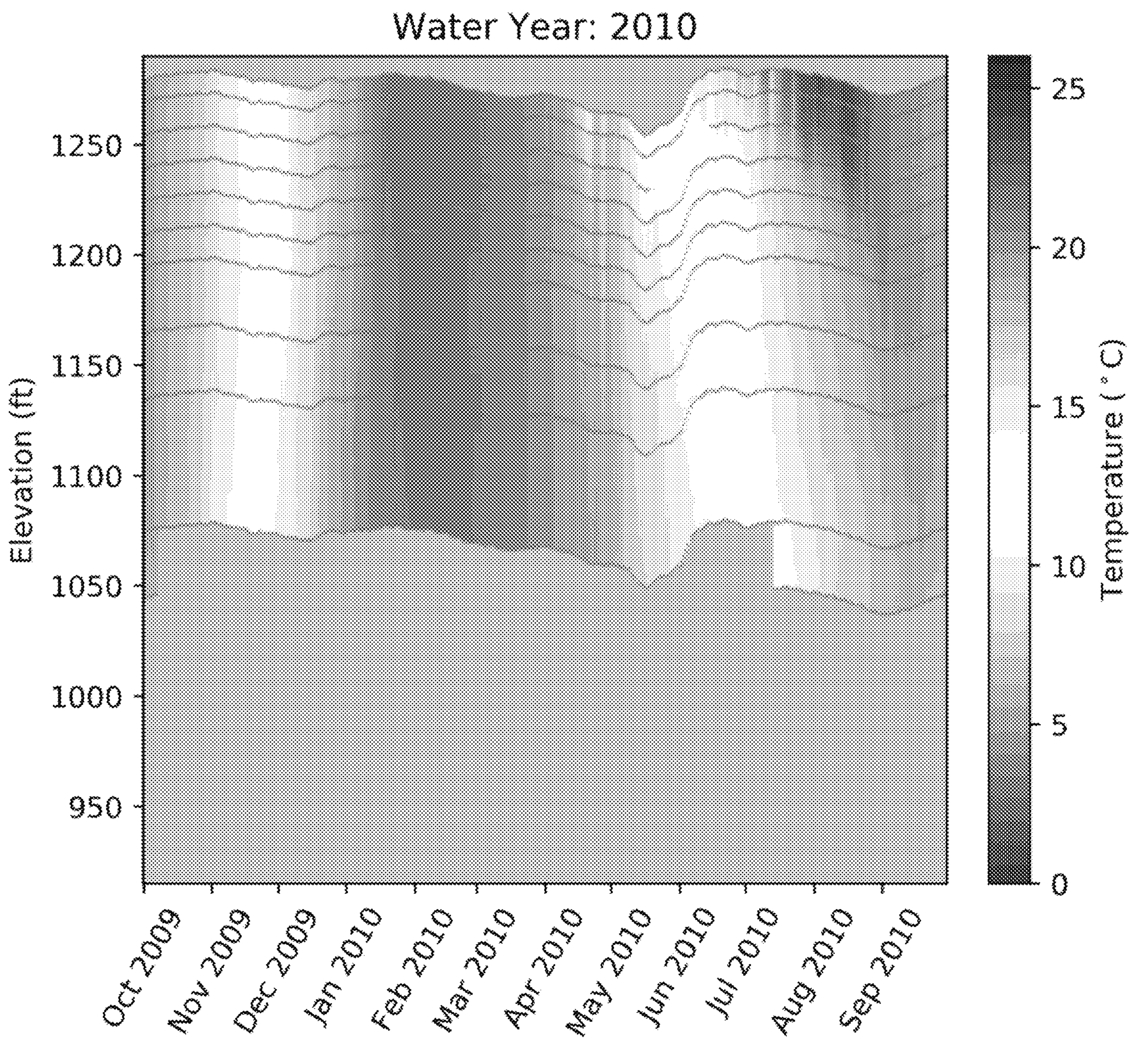
Water Year: 2010
Elevation (ft)
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1200
1150
1100
1050
1000
950
Oct 2009
Nov 2009
Dec 2009
Jan 2010
Feb 2010
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15
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5
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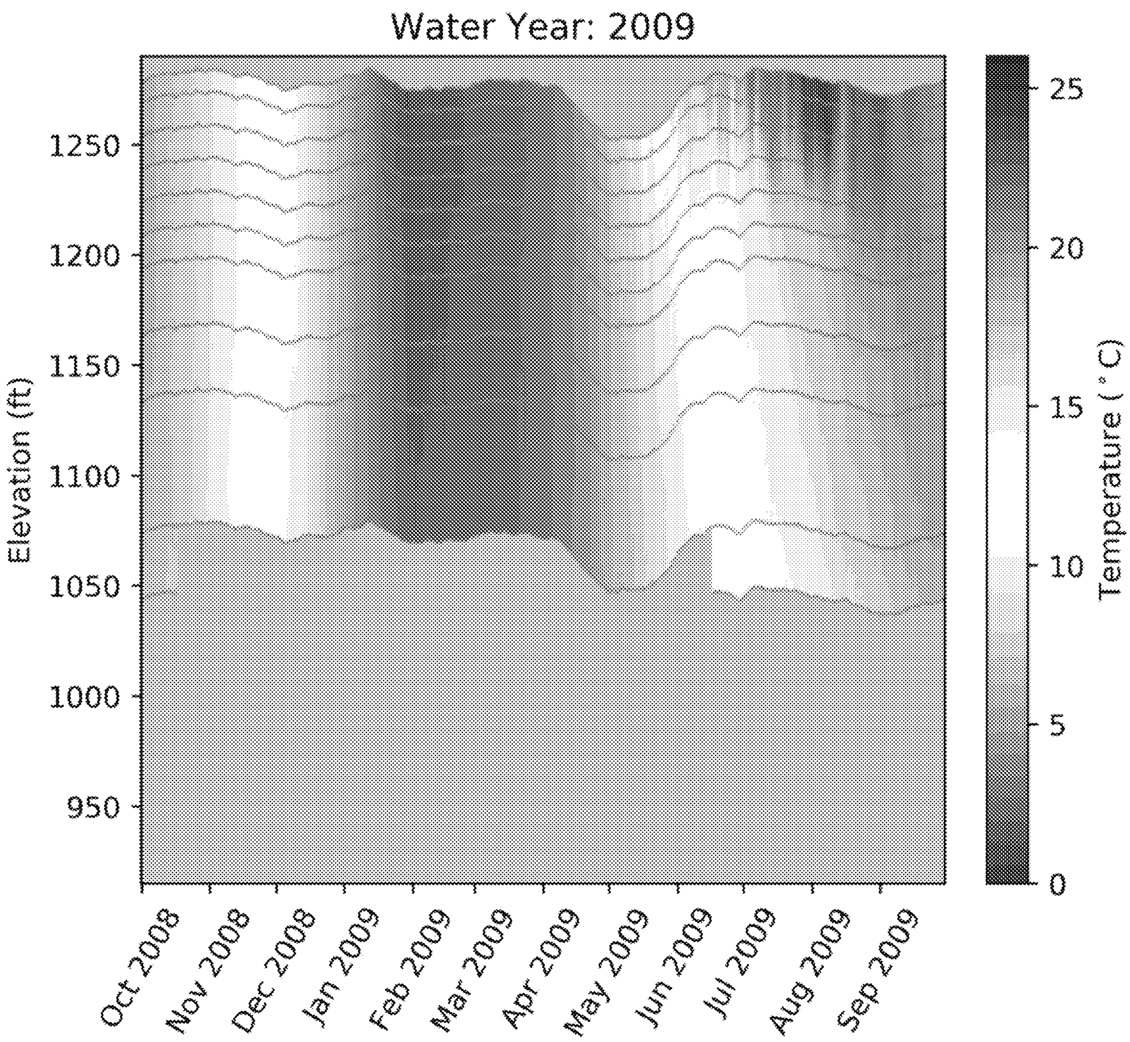
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1100
1050
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950
Oct 2008
Nov 2008
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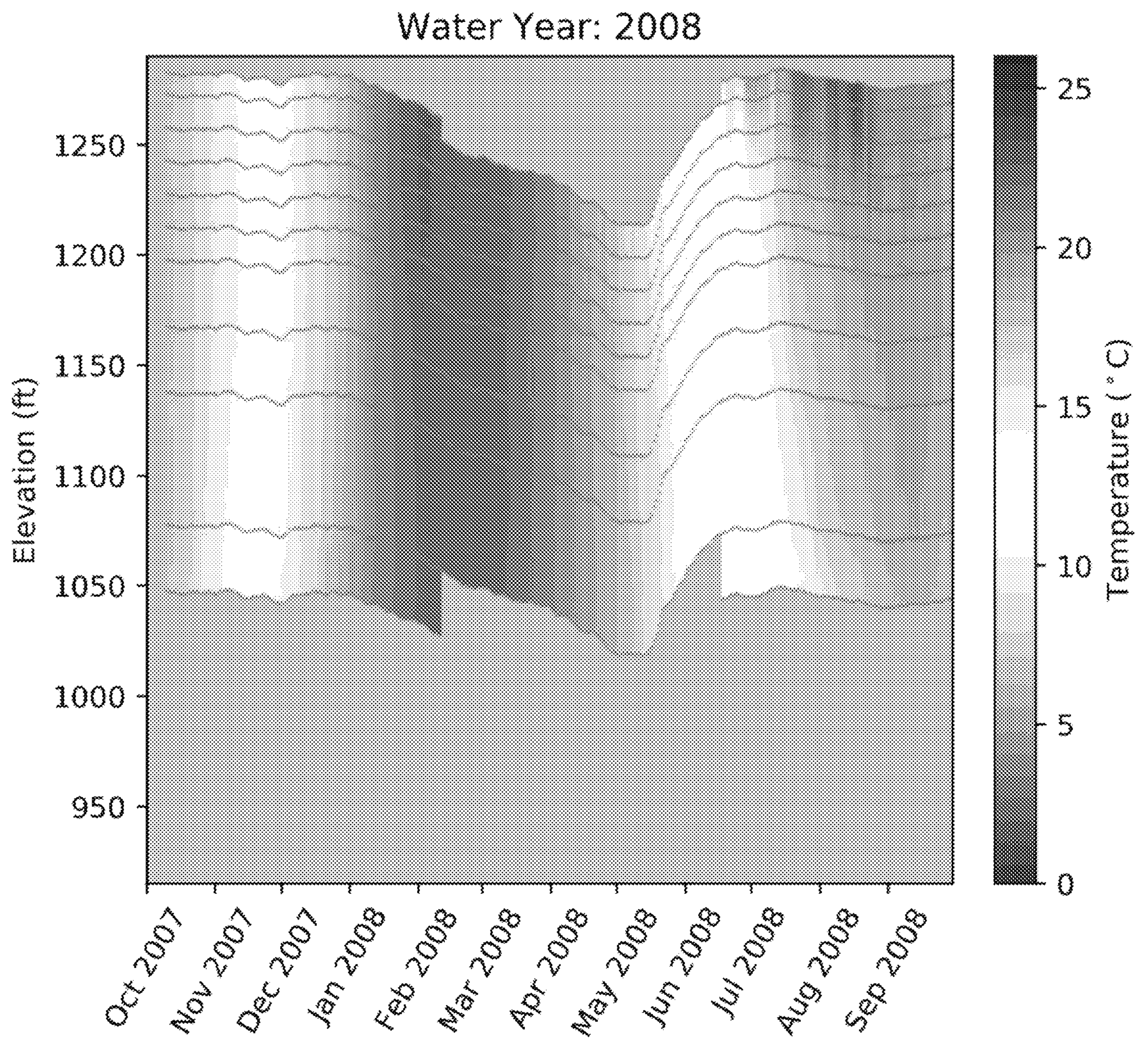
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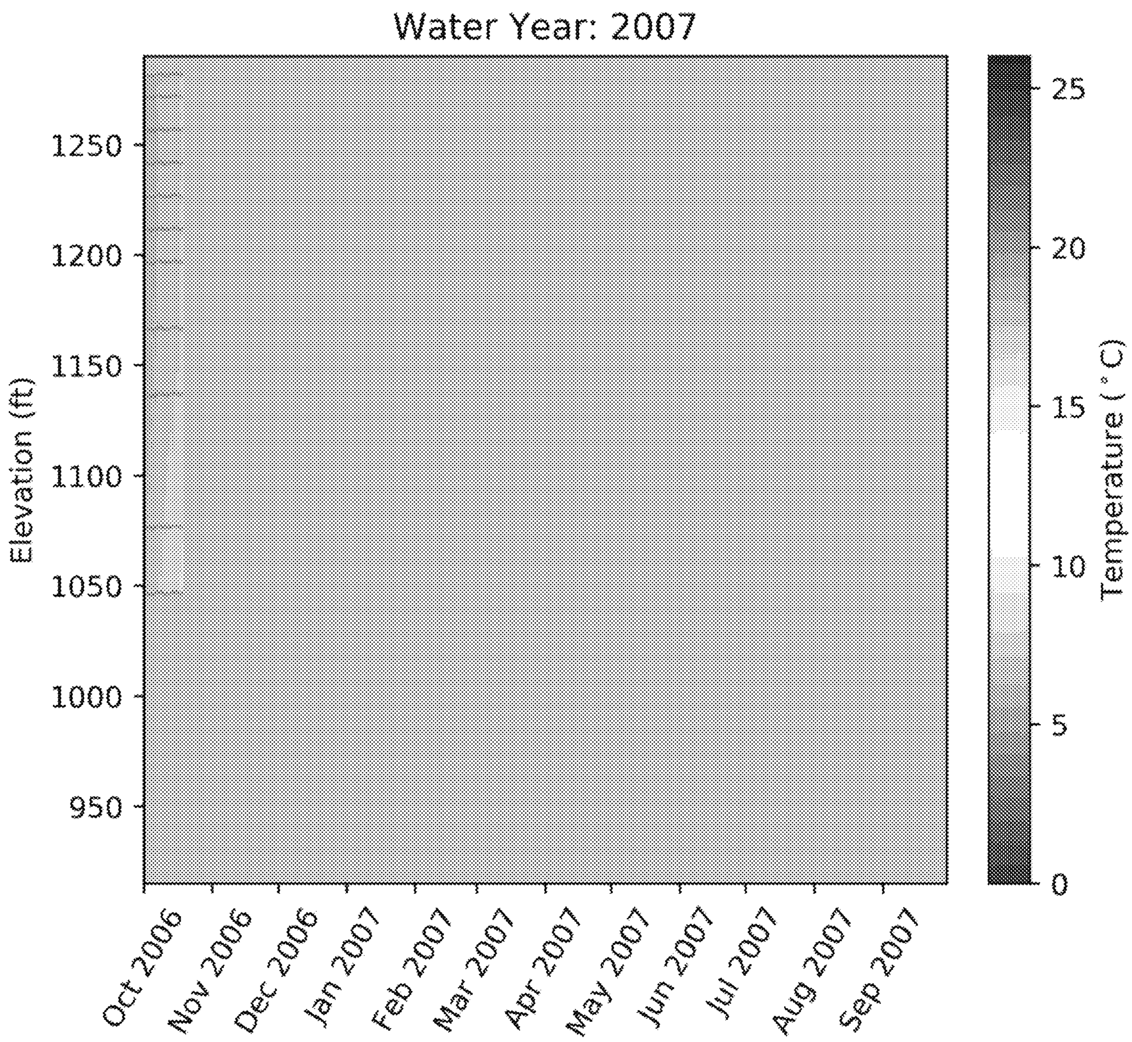
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1050
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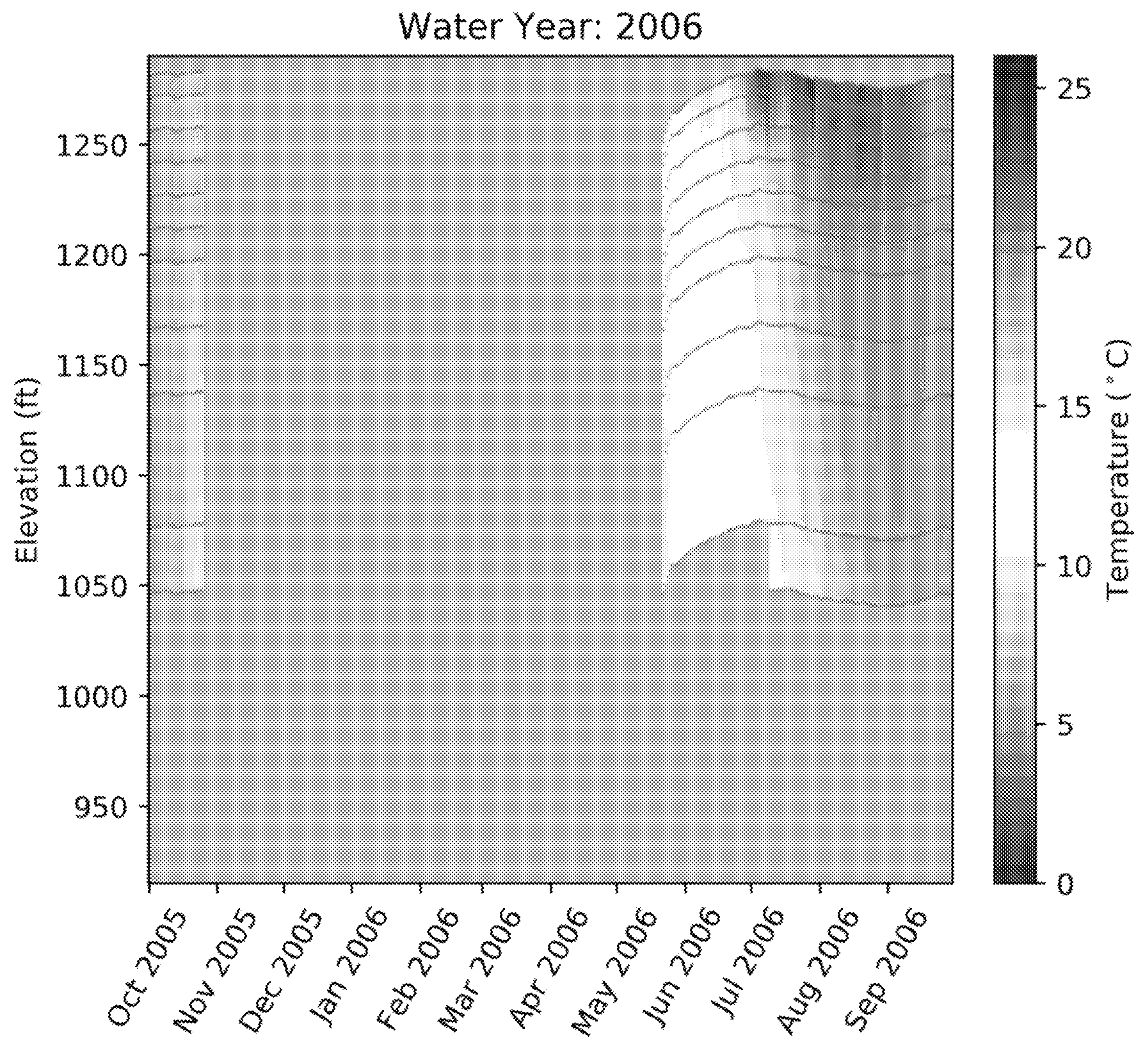

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1050
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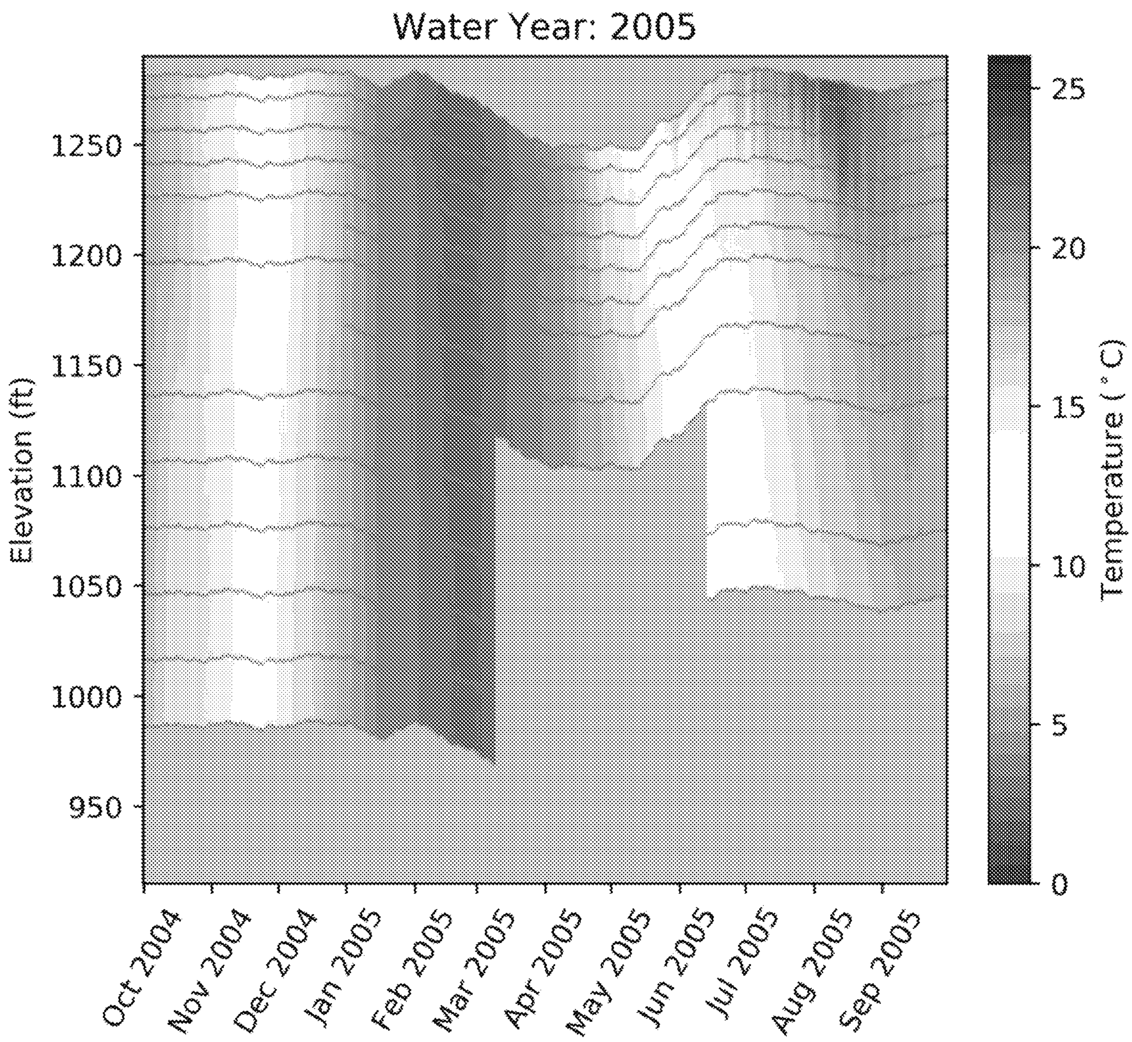
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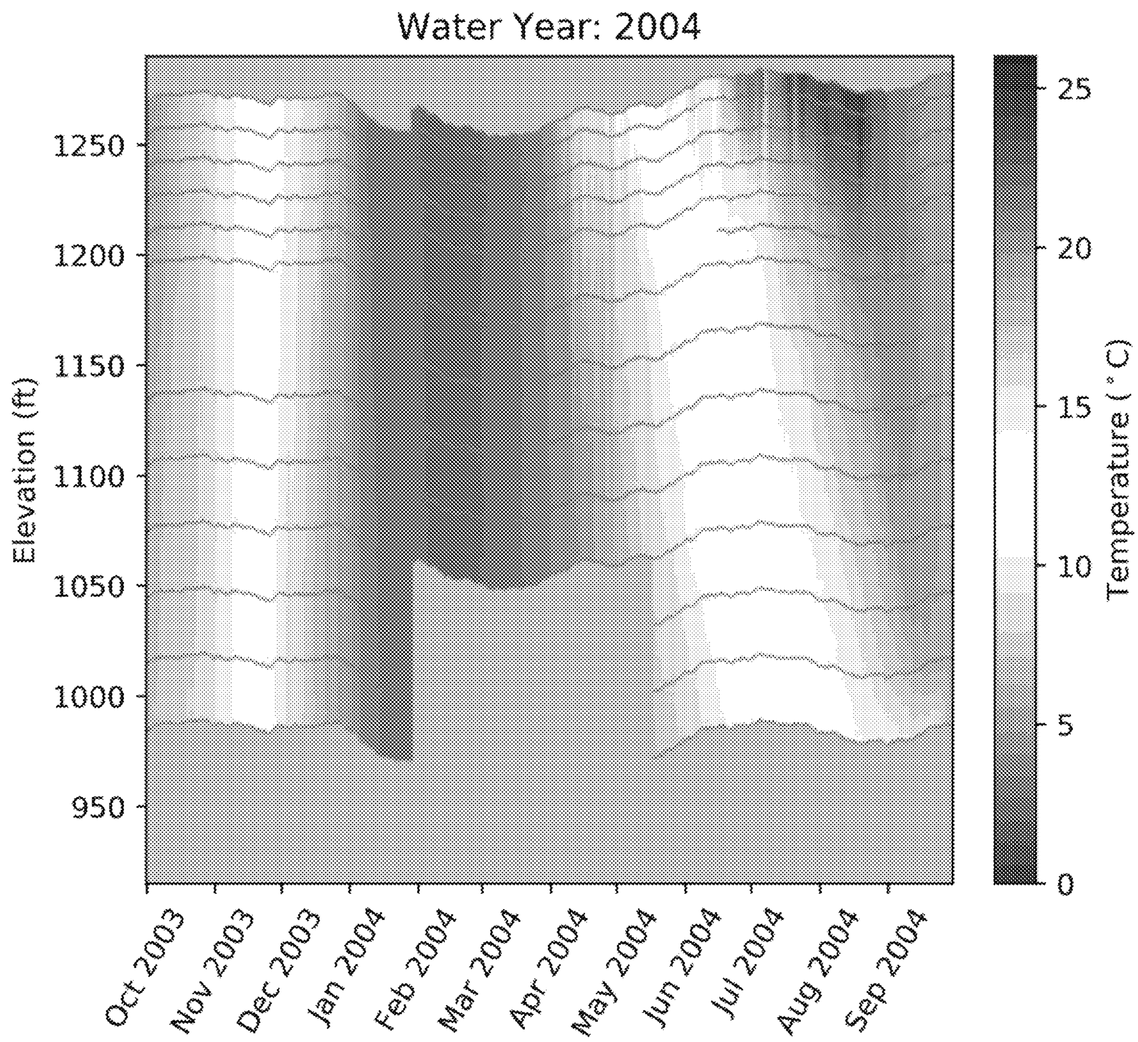
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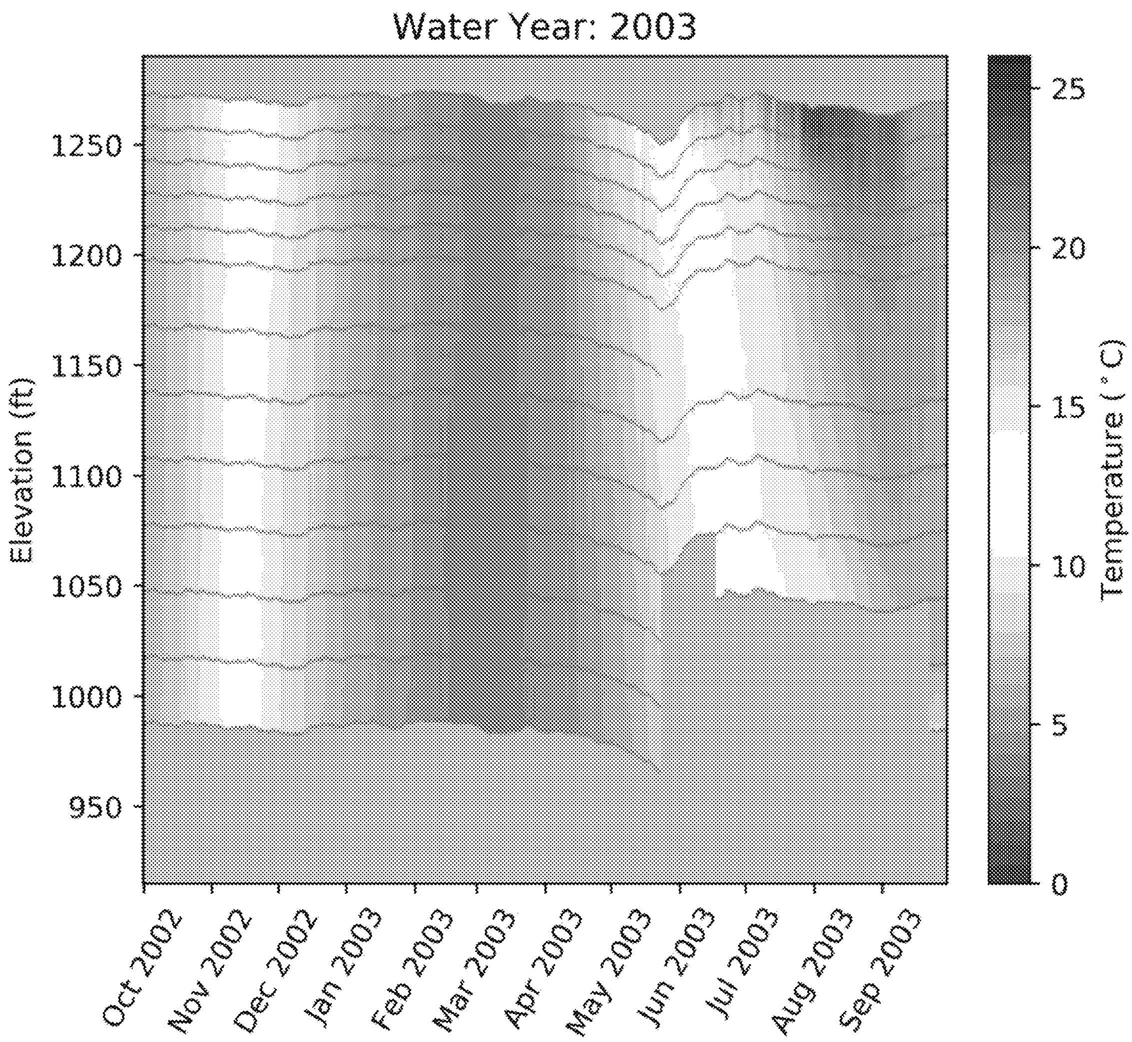

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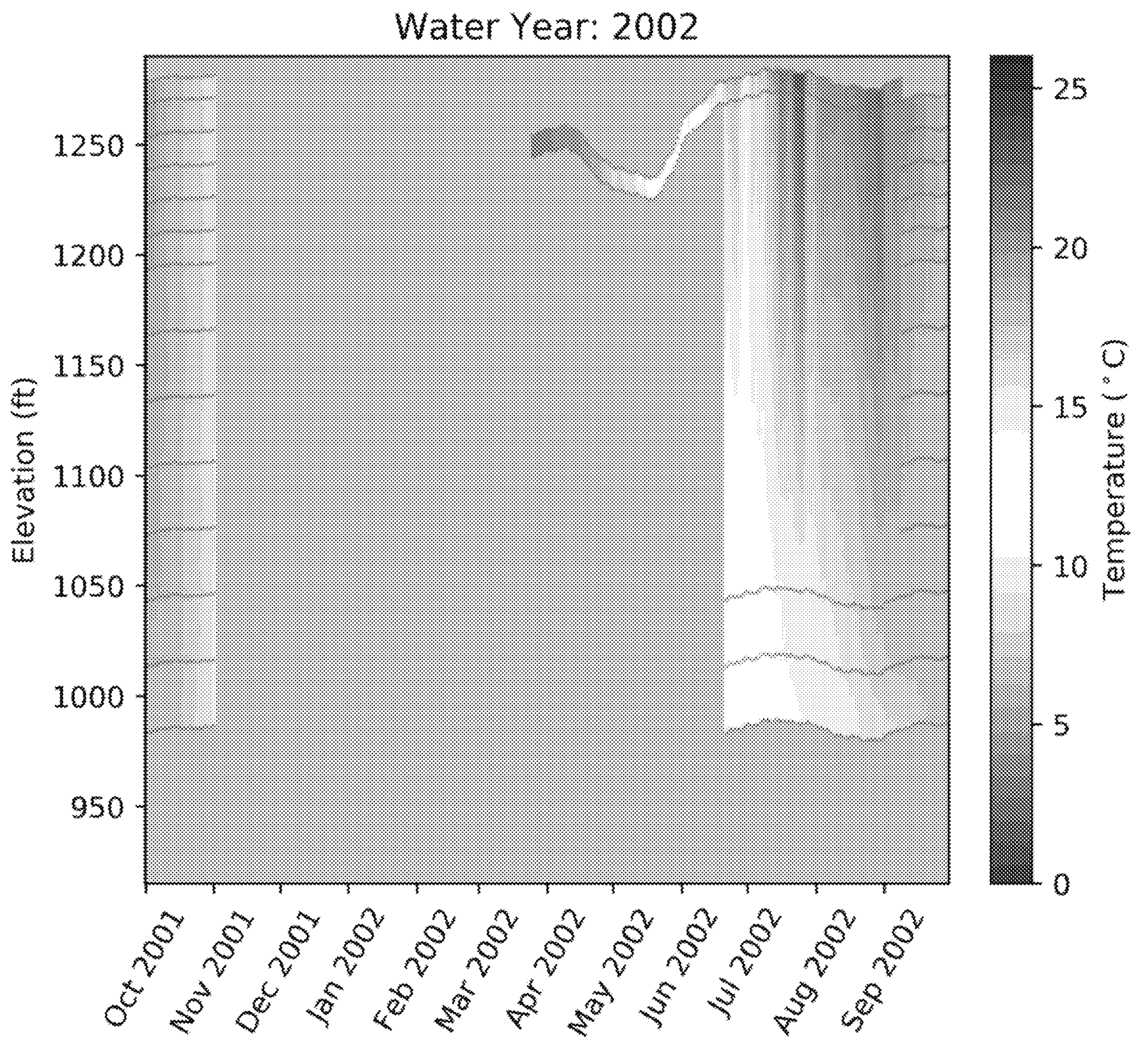
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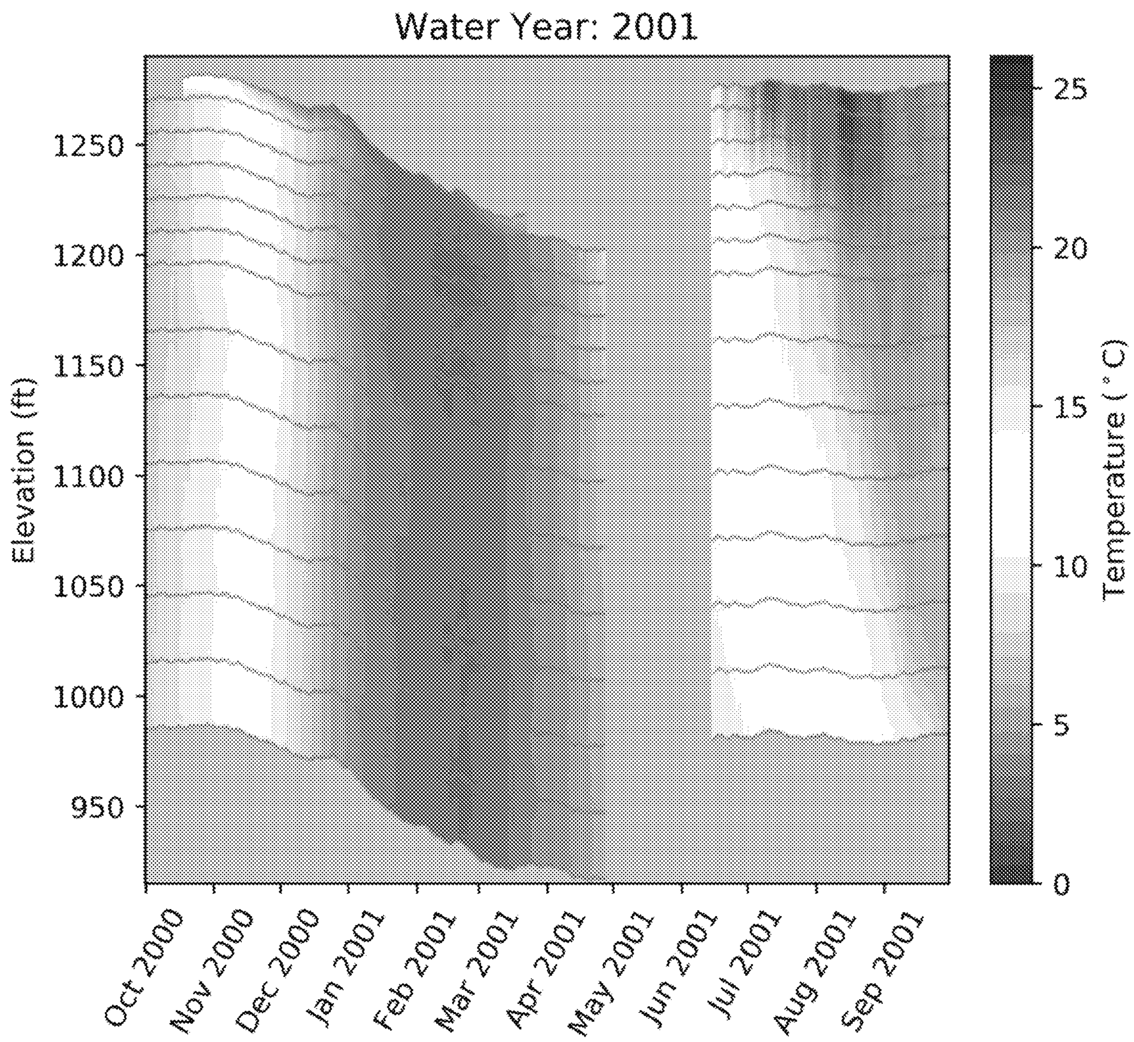
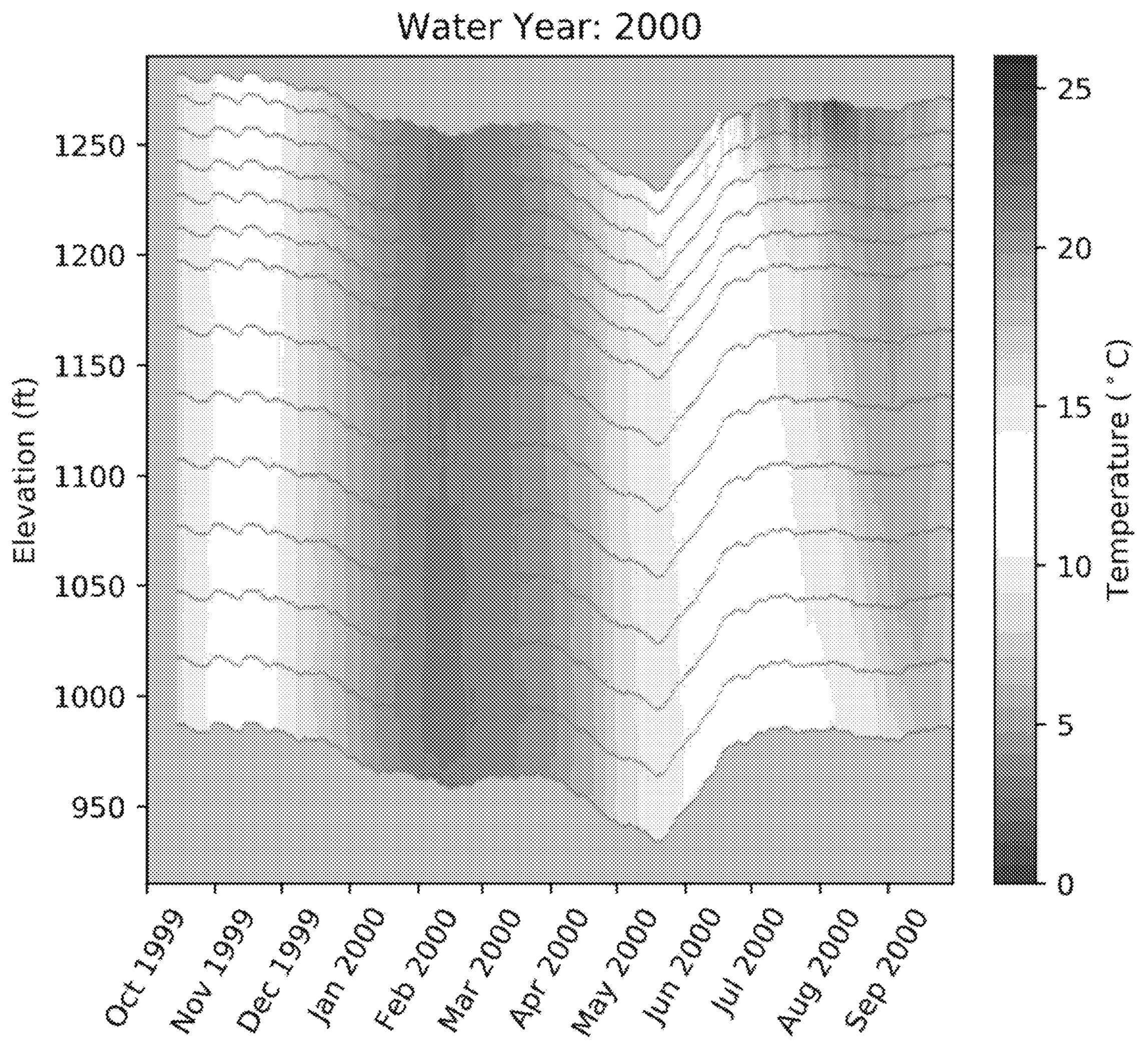
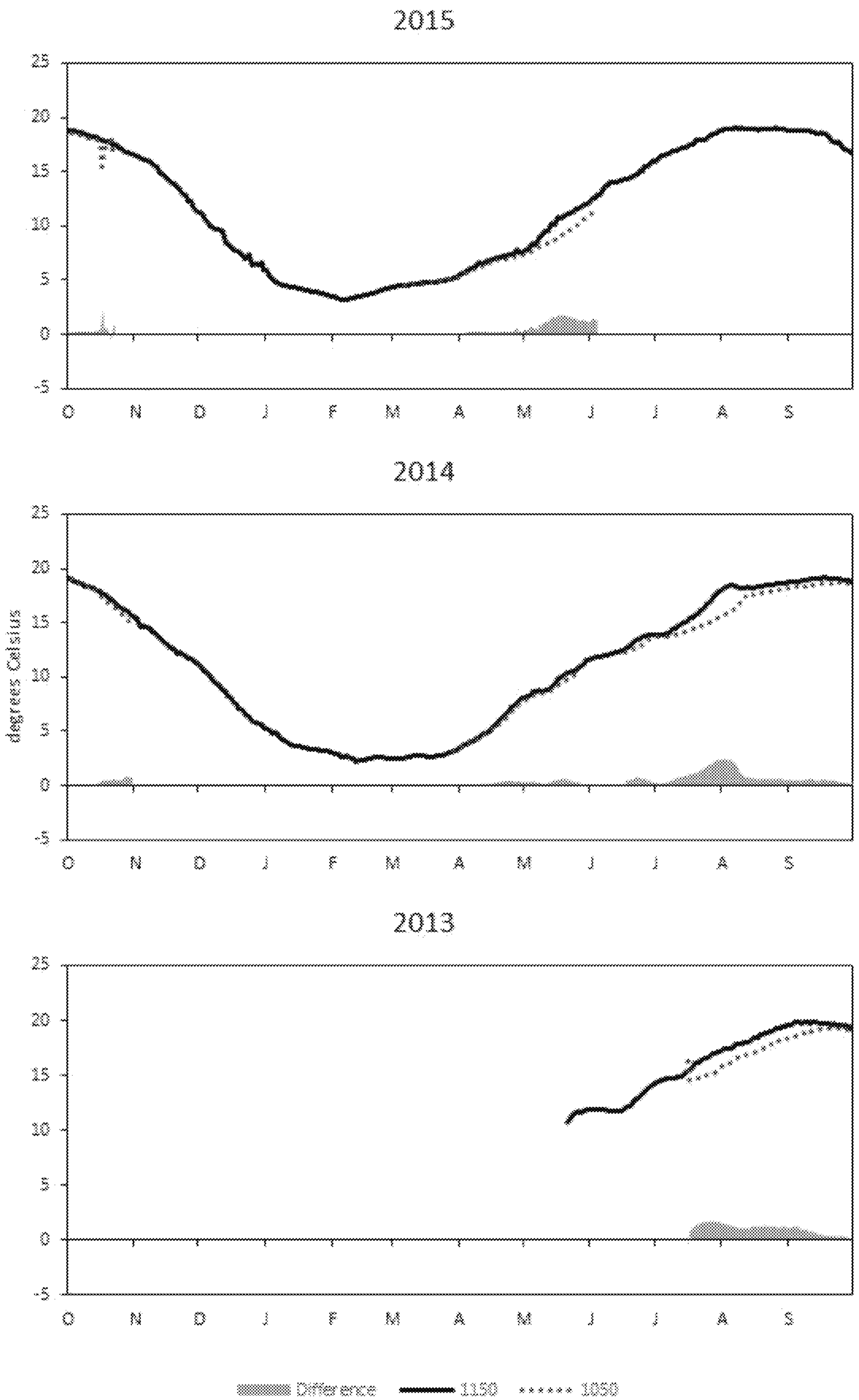
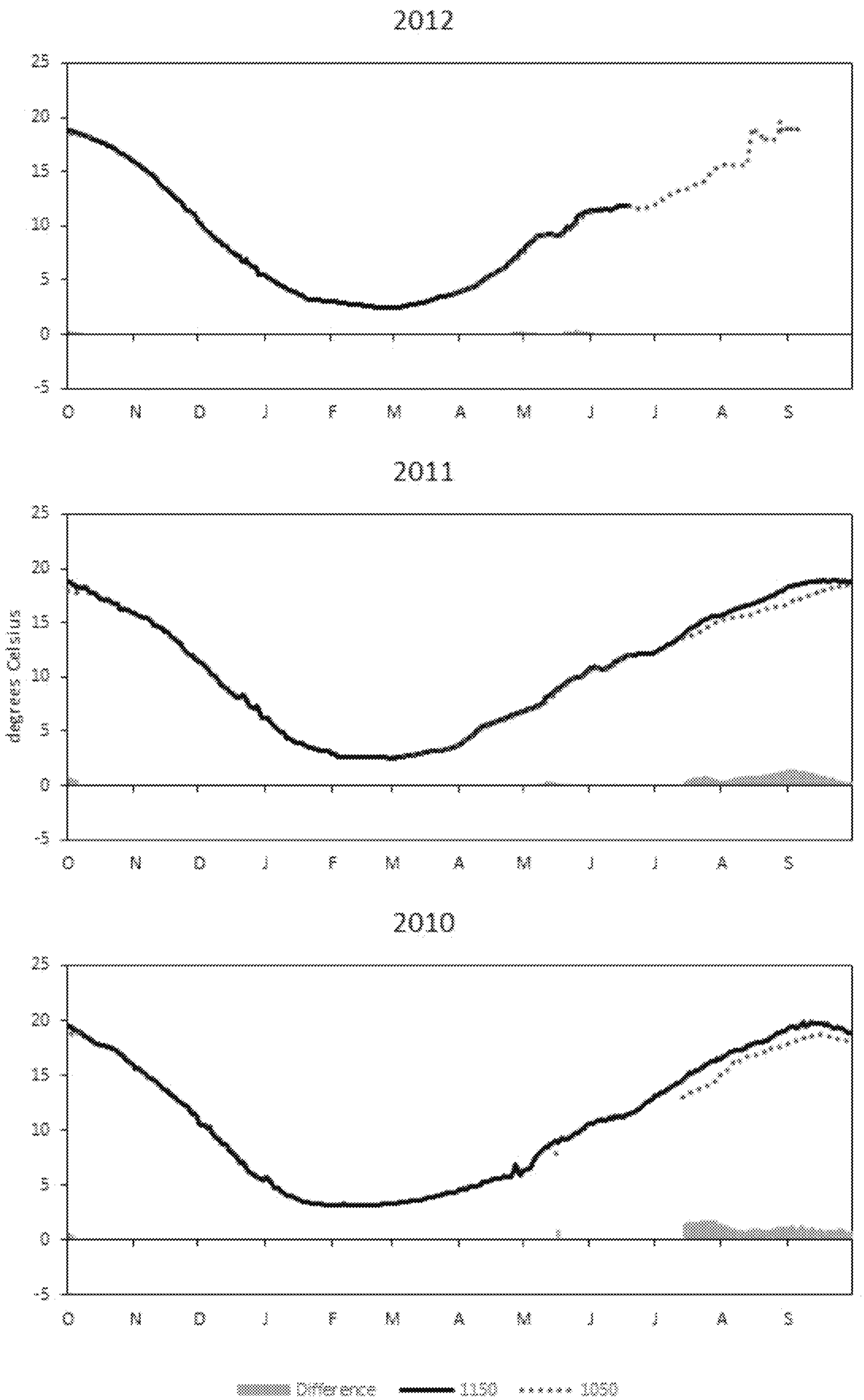

Water Year: 2001
Elevation (ft)
1250
1200
1150
1100
1050
1000
950
Oct 2000
Nov 2000
Dec 2000
Jan 2001
Feb 2001
Mar 2001
Apr 2001
May 2001
Jun 2001
Jul 2001
Aug 2001
Sep 2001
Temperature (°C)
25
20
15
10
5
0

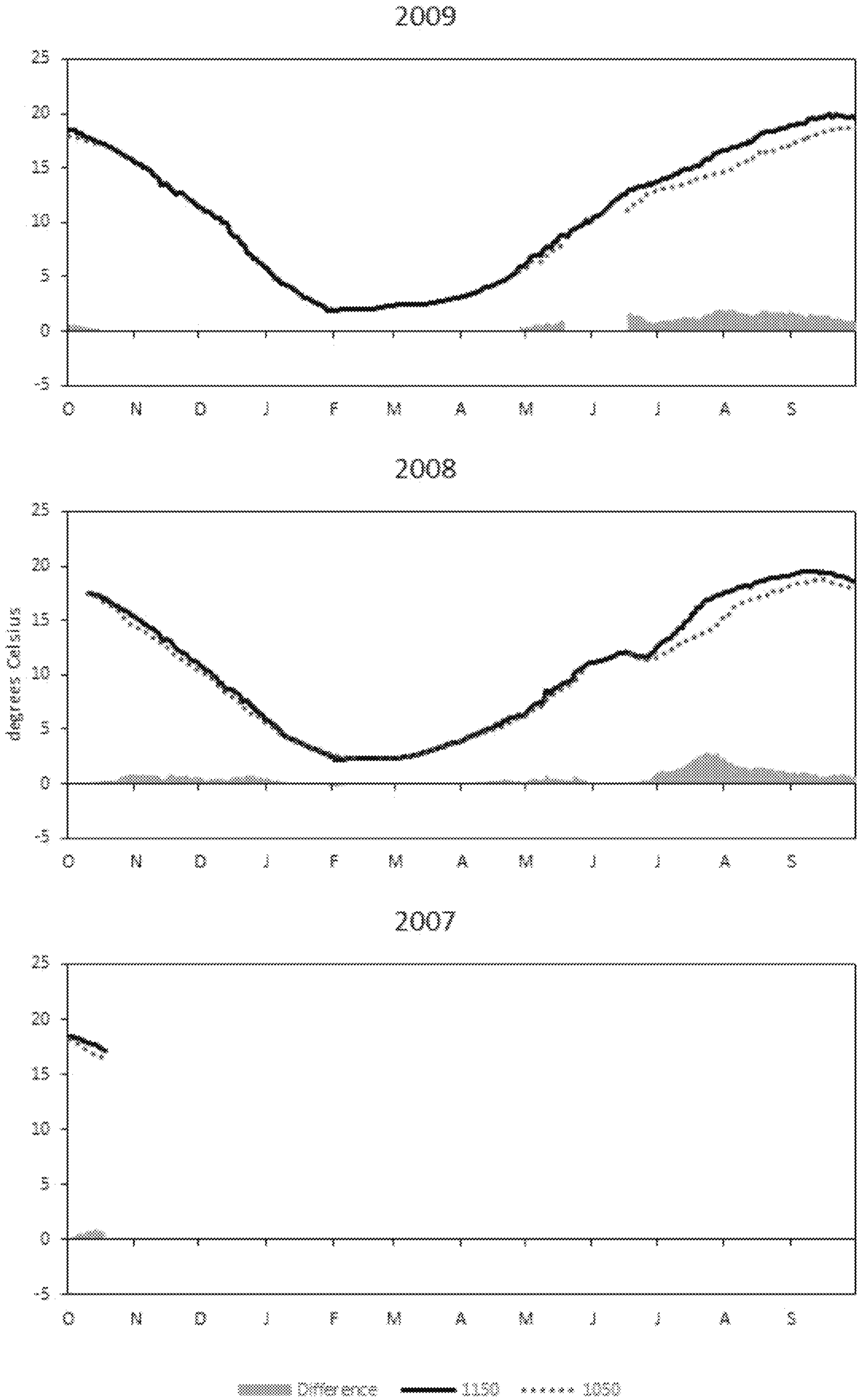


The following figures depict the temperatures at the approximate forebay elevations of the intakes for the Left and Right Powerhouses (1050 feet elevation is used here as an approximation of the pool temperature at this intake, the invert elevation is at 1040 feet) and the Third Powerhouses (1150 feet elevation is used here as an approximation of the pool temperature at this intake, the invert elevation is at 1140 feet). Ex. 5 Deliberative Process (DP)

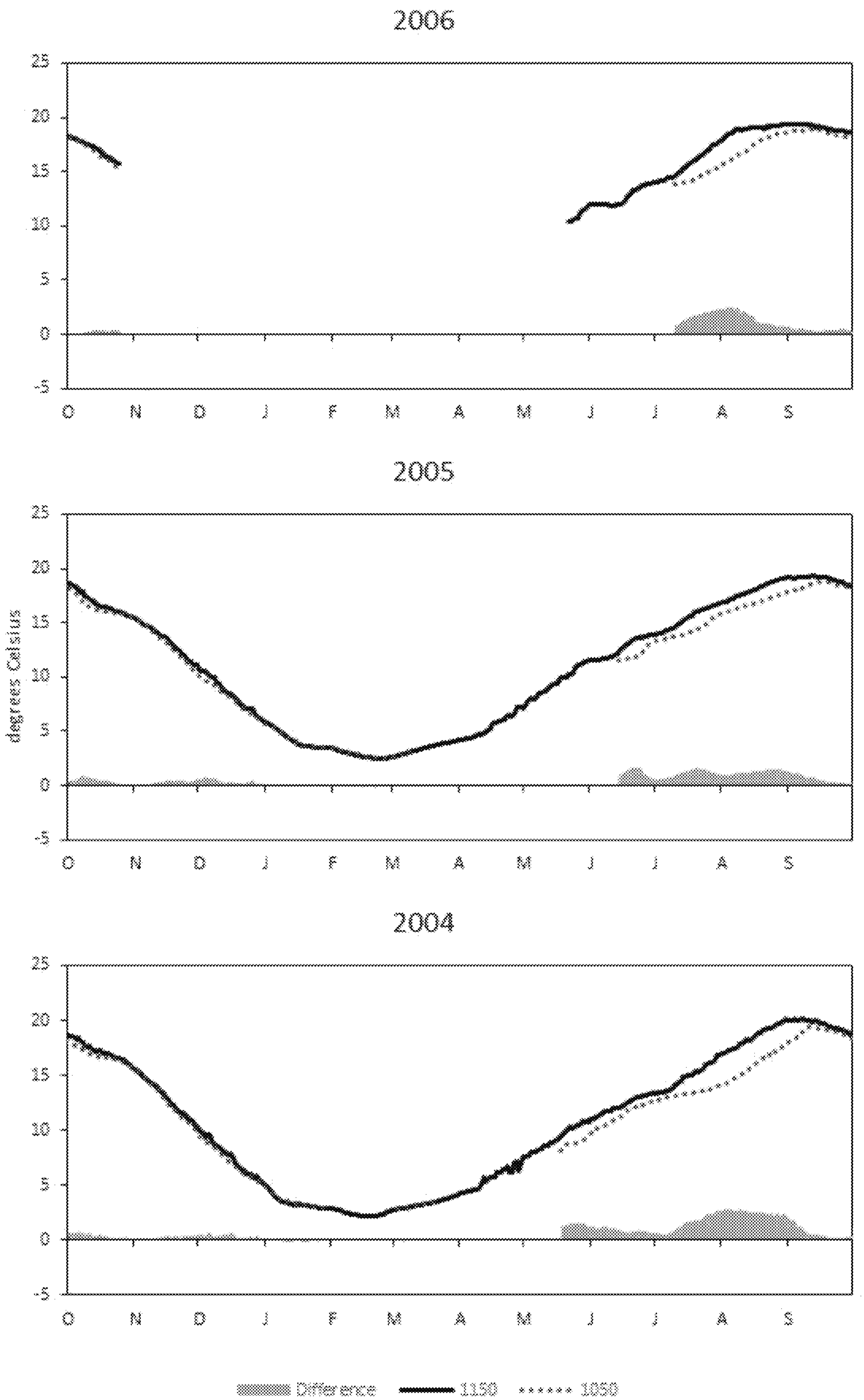
Ex. 5 Deliberative Process (DP)

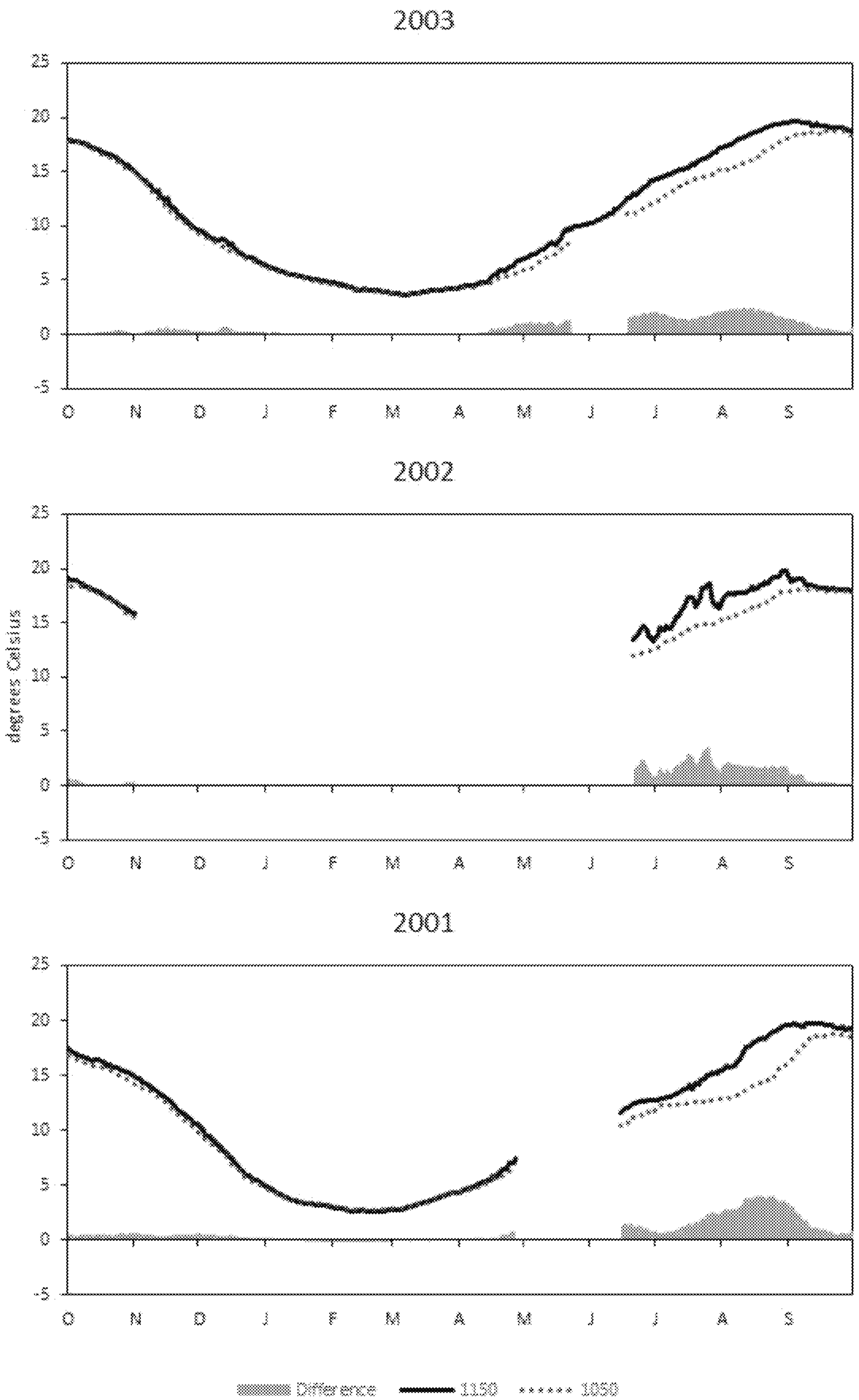

2015
2014
2013
degrees Celsius
25
20
15
10
5
0
-5
O N D J F M A M J J A S
Difference
1150
1050

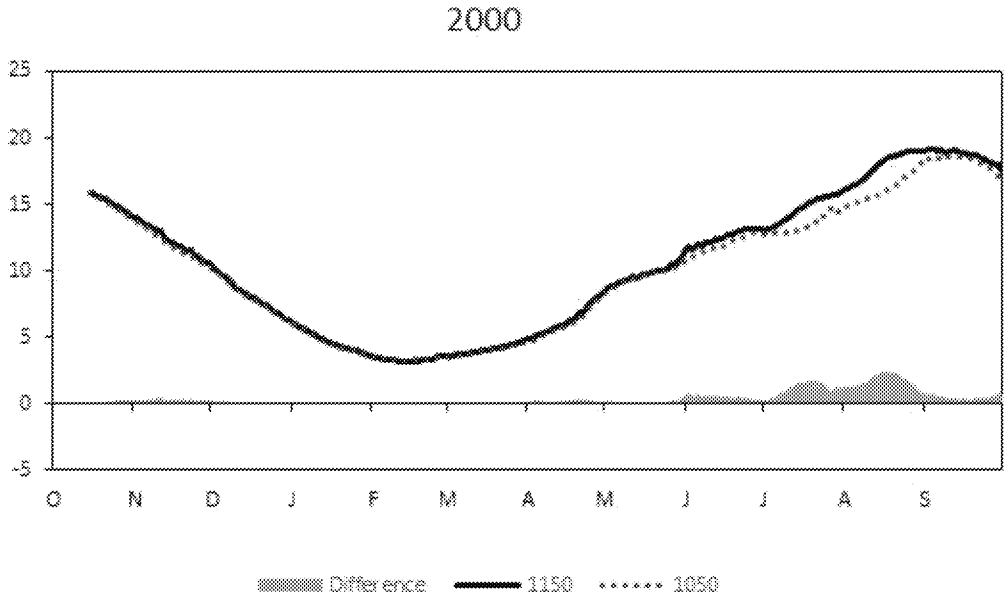

2012
2011
2010
degrees Celsius
25
20
15
10
5
0
-5
O
N
D
J
F
M
A
M
J
J
A
S
Difference
1150
1050



ED_004421A_00650619-00061


2006
25
20
15
10
5
0
-5
O N D J F M A M J J A S
2005
degrees Celsius
2004
Difference
1150
1050


2003
2002
2001
degrees Celsius
25
20
15
10
5
0
-5
O
N
D
J
F
M
A
M
J
J
A
S
Difference
1150
1050

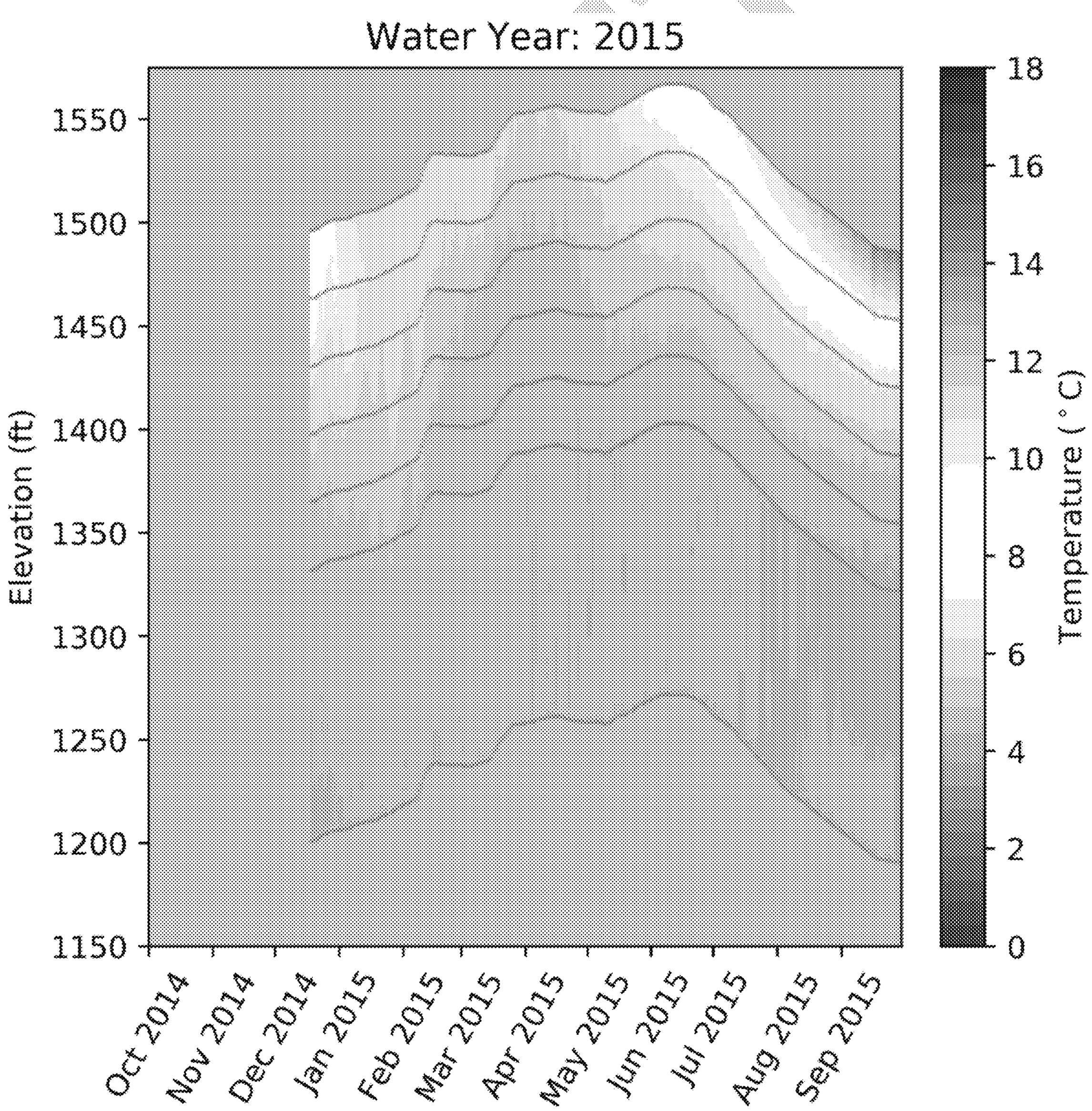

2000
25
20
15
10
5
0
-5
O
N
D
J
F
M
A
M
J
J
A
S
Difference
1150
1050

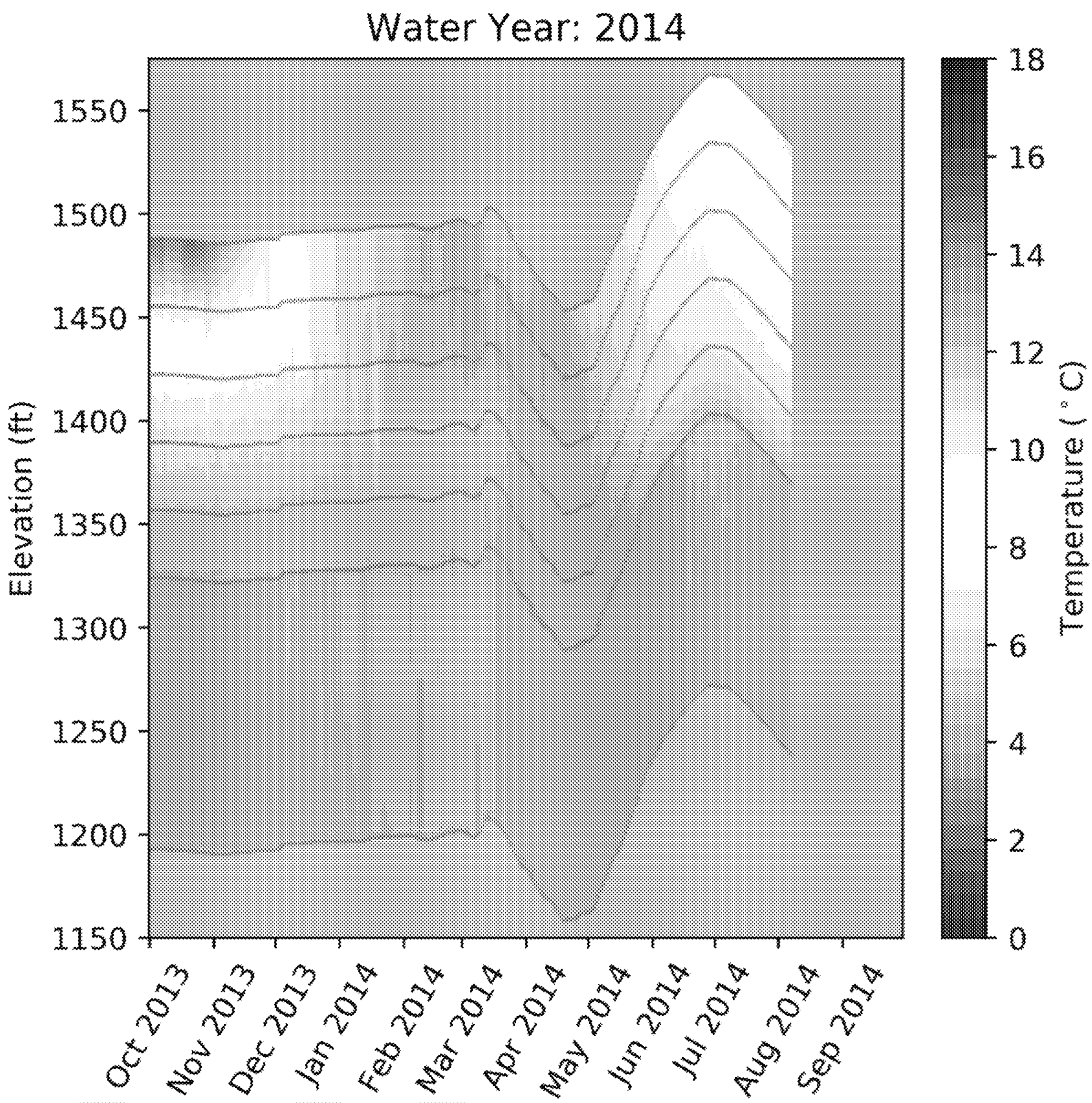
6 APPENDIX B: DWORSHAK DAM AND RESERVOIR STRATIFICATION

Ex. 5 Deliberative Process (DP)

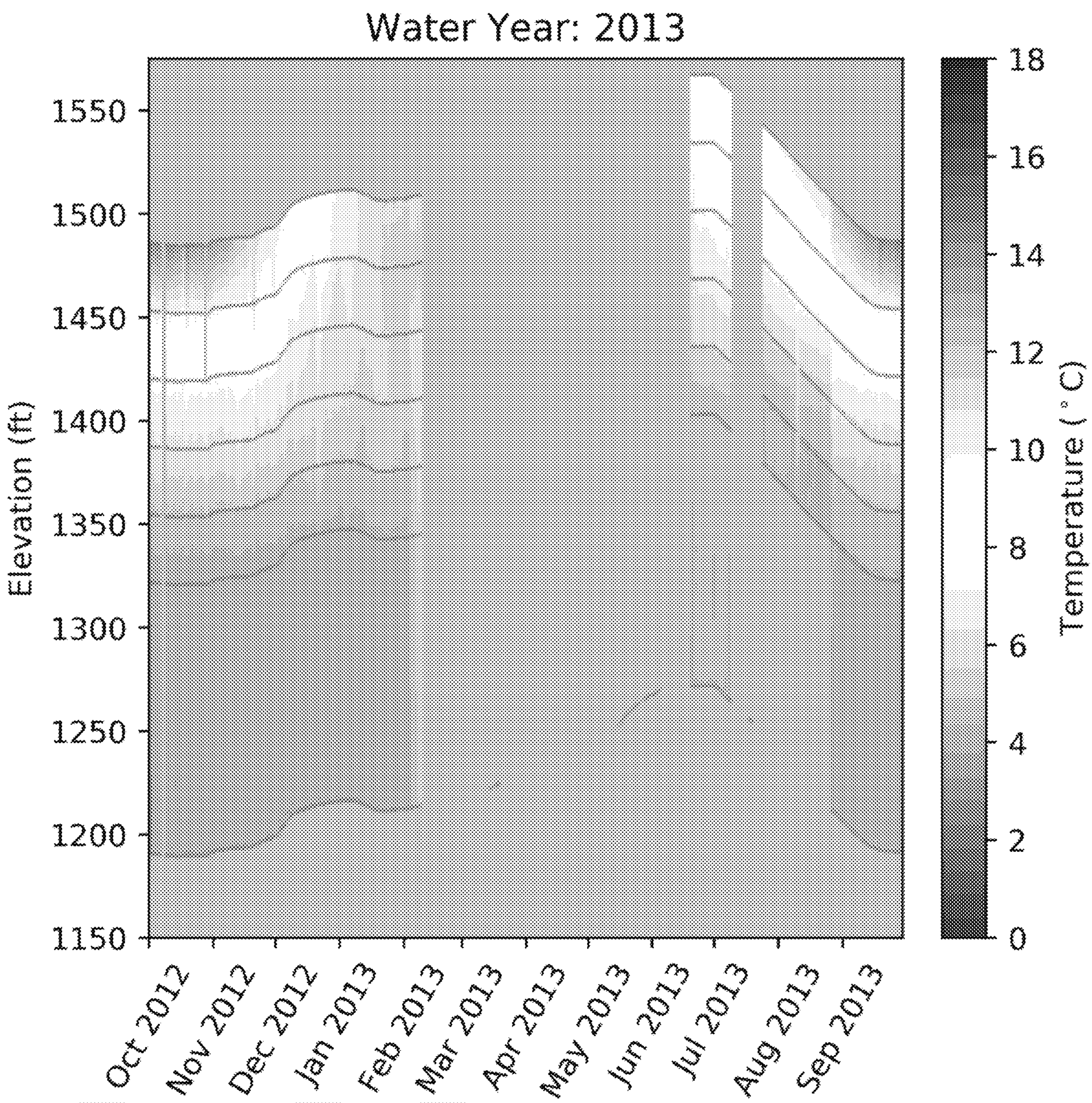
Ex. 5 Deliberative Process (DP) Operations of Dworshak Dam take advantage of this stratification to reduce temperatures in the lower Snake River by releasing cooler stored water in the Clearwater River.

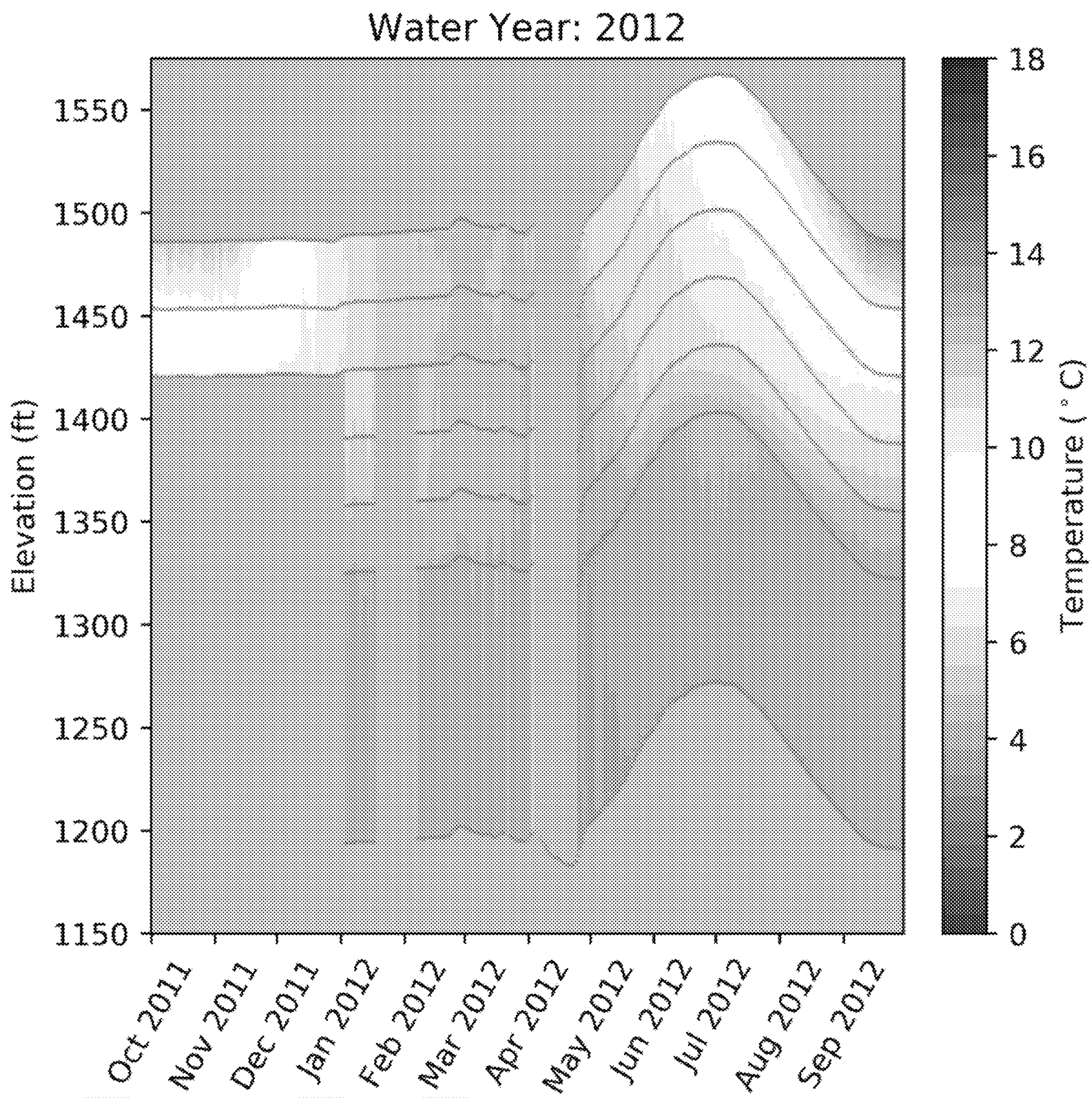
Below are figures of pool temperatures behind Dworshak Dam for water years 2006 through 2015, the color scale represents 0 to 18°C, grey is missing data.

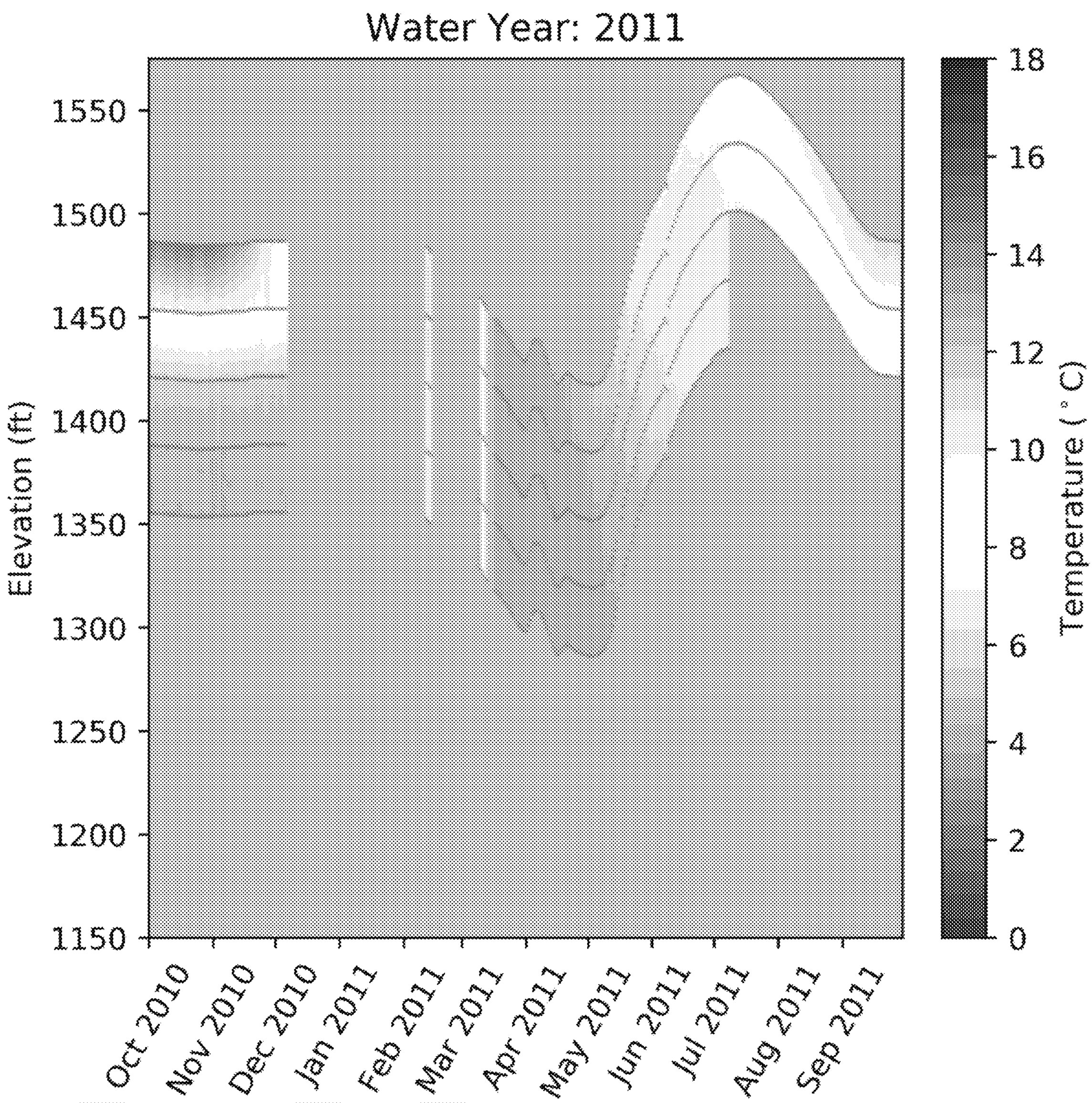


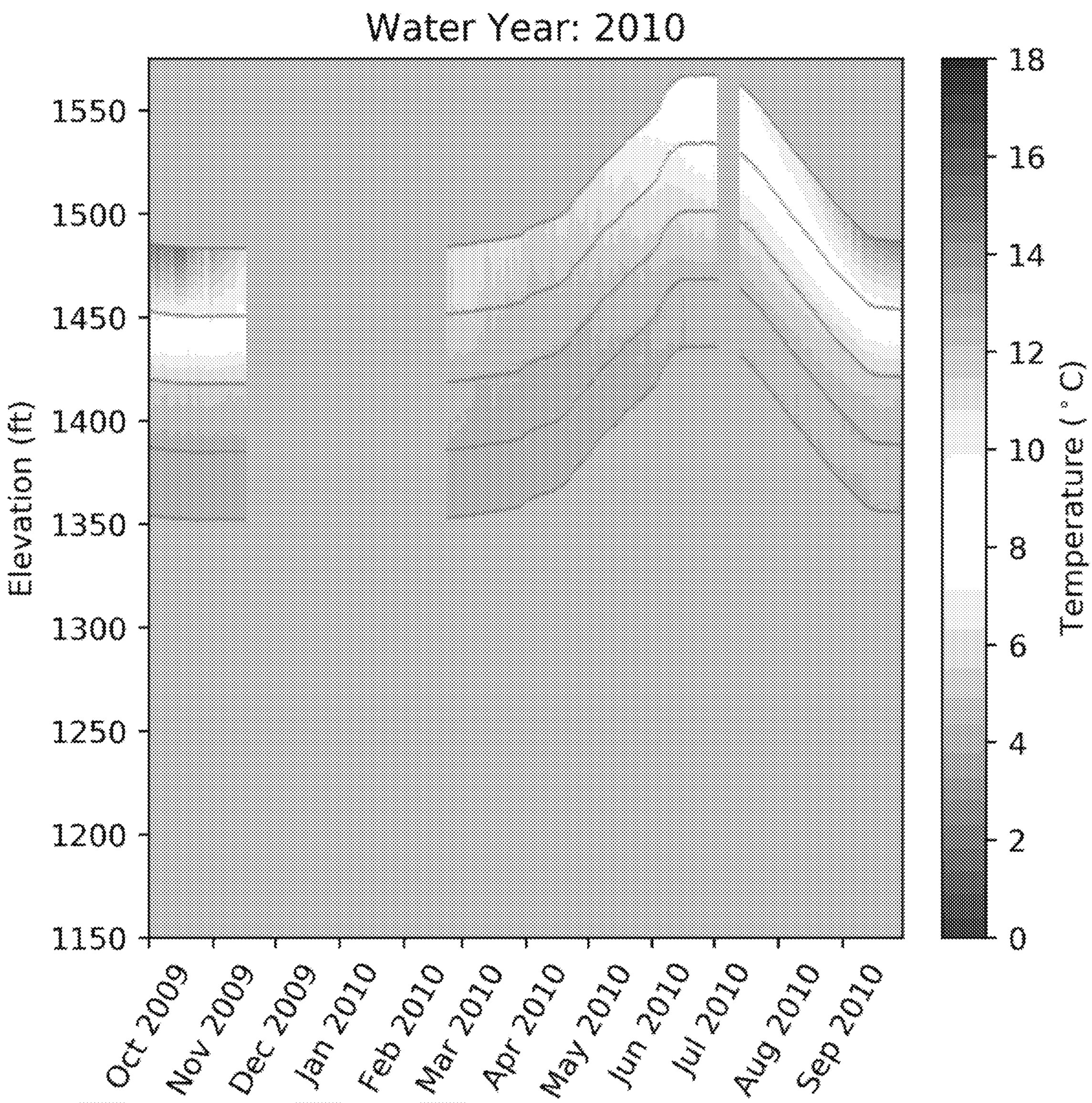


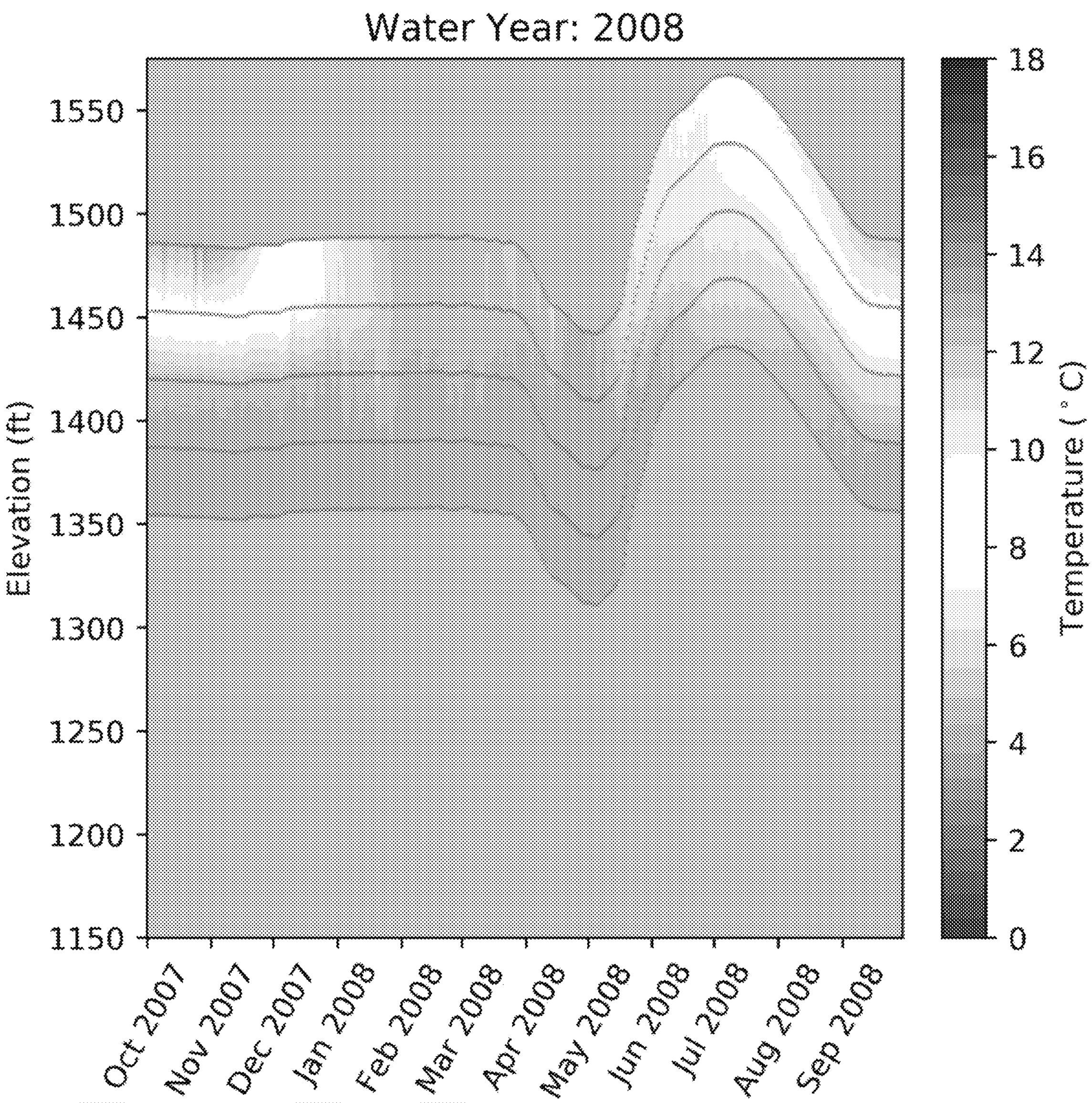
Water Year: 2014
Elevation (ft)
1550
1500
1450
1400
1350
1300
1250
1200
1150
Oct 2013
Nov 2013
Dec 2013
Jan 2014
Feb 2014
Mar 2014
Apr 2014
May 2014
Jun 2014
Jul 2014
Aug 2014
Sep 2014
Temperature (°C)
18
16
14
12
10
8
6
4
2
0

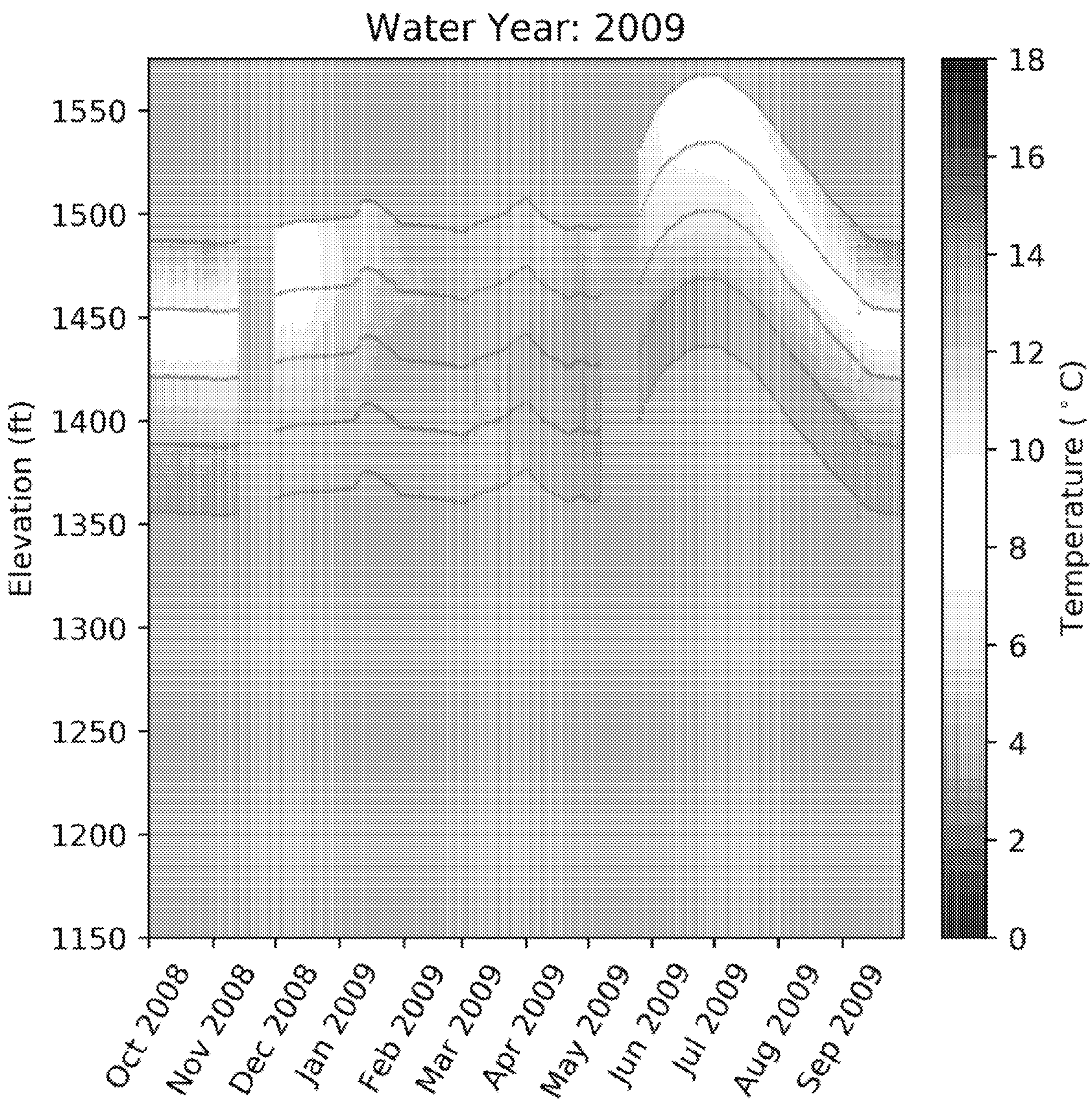

Water Year: 2013
Elevation (ft)
1550
1500
1450
1400
1350
1300
1250
1200
1150
Oct 2012
Nov 2012
Dec 2012
Jan 2013
Feb 2013
Mar 2013
Apr 2013
May 2013
Jun 2013
Jul 2013
Aug 2013
Sep 2013
Temperature ($^\circ$ C)
18
16
14
12
10
8
6
4
2
0

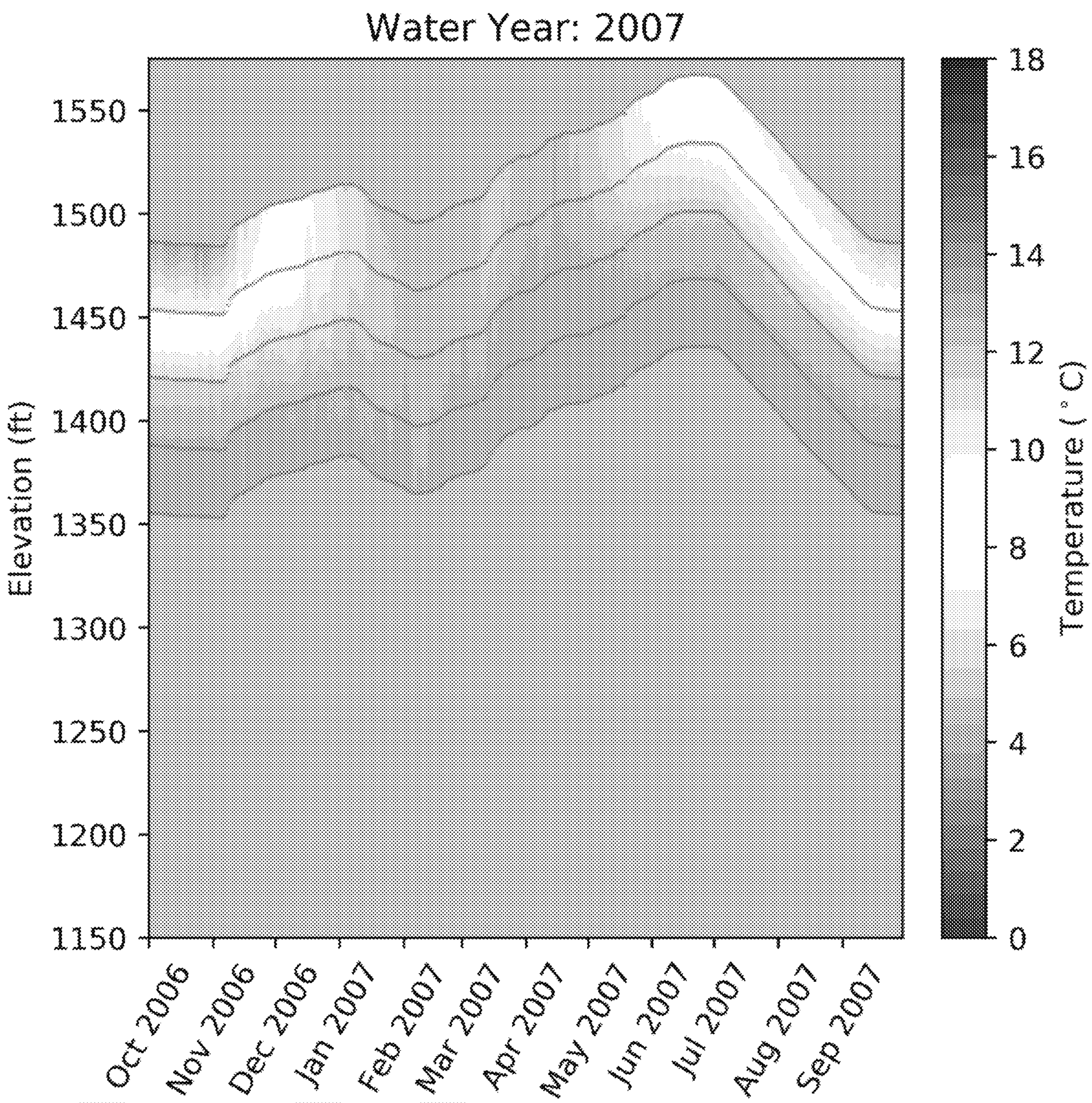

Water Year: 2012
Elevation (ft)
1550
1500
1450
1400
1350
1300
1250
1200
1150
Oct 2011
Nov 2011
Dec 2011
Jan 2012
Feb 2012
Mar 2012
Apr 2012
May 2012
Jun 2012
Jul 2012
Aug 2012
Sep 2012
Temperature ($^\circ$C)
18
16
14
12
10
8
6
4
2
0

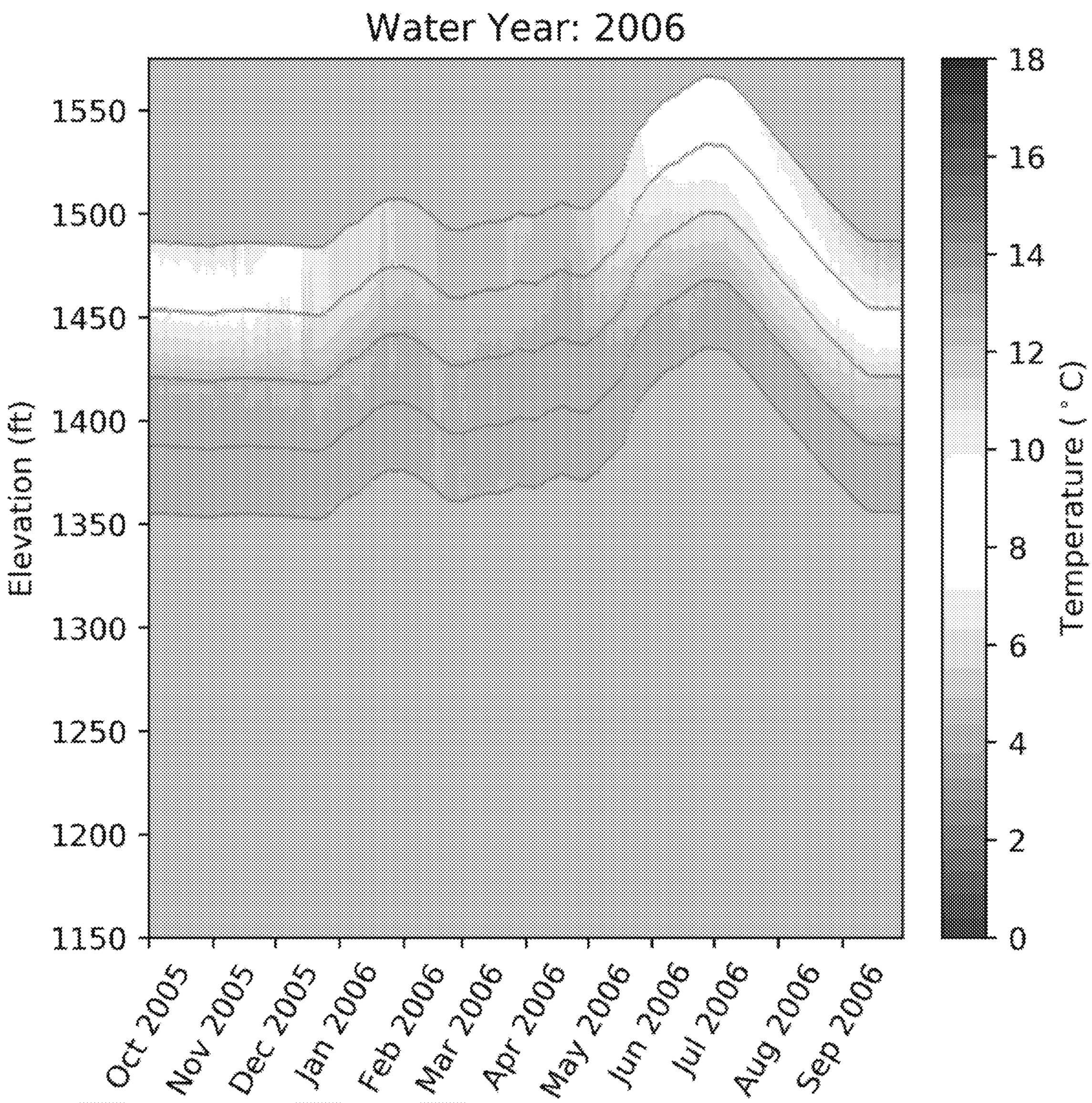

Water Year: 2011
Elevation (ft)
1550
1500
1450
1400
1350
1300
1250
1200
1150
Oct 2010
Nov 2010
Dec 2010
Jan 2011
Feb 2011
Mar 2011
Apr 2011
May 2011
Jun 2011
Jul 2011
Aug 2011
Sep 2011
Temperature ($^\circ$ C)
18
16
14
12
10
8
6
4
2
0


Water Year: 2010
Elevation (ft)
1550
1500
1450
1400
1350
1300
1250
1200
1150
Oct 2009
Nov 2009
Dec 2009
Jan 2010
Feb 2010
Mar 2010
Apr 2010
May 2010
Jun 2010
Jul 2010
Aug 2010
Sep 2010
Temperature (° C)
18
16
14
12
10
8
6
4
2
0


Water Year: 2008
Elevation (ft)
1550
1500
1450
1400
1350
1300
1250
1200
1150
Oct 2007
Nov 2007
Dec 2007
Jan 2008
Feb 2008
Mar 2008
Apr 2008
May 2008
Jun 2008
Jul 2008
Aug 2008
Sep 2008
Temperature (° C)
18
16
14
12
10
8
6
4
2
0


Water Year: 2009
1550
1500
1450
1400
1350
1300
1250
1200
1150
Elevation (ft)
Oct 2008
Nov 2008
Dec 2008
Jan 2009
Feb 2009
Mar 2009
Apr 2009
May 2009
Jun 2009
Jul 2009
Aug 2009
Sep 2009
18
16
14
12
10
8
6
4
2
0
Temperature (°C)


Water Year: 2007
Elevation (ft)
1550
1500
1450
1400
1350
1300
1250
1200
1150
Oct 2006
Nov 2006
Dec 2006
Jan 2007
Feb 2007
Mar 2007
Apr 2007
May 2007
Jun 2007
Jul 2007
Aug 2007
Sep 2007
Temperature ($^\circ$C)
18
16
14
12
10
8
6
4
2
0


Water Year: 2006
Elevation (ft)
1550
1500
1450
1400
1350
1300
1250
1200
1150
Oct 2005
Nov 2005
Dec 2005
Jan 2006
Feb 2006
Mar 2006
Apr 2006
May 2006
Jun 2006
Jul 2006
Aug 2006
Sep 2006
Temperature ($^\circ$C)
18
16
14
12
10
8
6
4
2
0